

Incorporating GHG Mitigation into Ontario Highway Pavement Engineering Practices

by
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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Greenhouse Gas (GHG) emissions are main concern for many national and international agencies. Increased human activities and growth in all sectors are affecting our society in a positive way but also putting our future generations at risk by affecting the environment through increases in GHG emissions.

The transportation sector has been shown to be the second largest contributor to Canada's total GHG emissions with Ontario being the second largest contributor of GHG emissions among all the provinces of Canada. In 2016, the Ministry of Transportation of Ontario (MTO) published its strategy and commitment to minimize the GHG emissions by 80% below the 1990 levels by 2050. In Ontario, the transportation sector accounts for almost 35% of GHG emissions.

In addition to increased emissions, increased traffic volumes and loads are putting extra demand on the existing pavement system. Canada faces many challenges in maintaining road transportation infrastructure as the roads are aging and there are limited funds available for maintenance and repairs. Traffic volumes and vehicle loads continue to increase, putting even more demand on the already stressed pavement system in major metropolitan areas and resulting in serious congestion problems. These challenges force road agencies to form innovative ways to sustain and develop new transportation infrastructure. As our highway infrastructure ages, the transportation industry needs to find alternatives or strategies of building, maintaining and reconstructing road infrastructure that is cost effective and minimizes the environmental impact.

This research is to identify strategies that are currently used in the road construction industry by different jurisdictions which may show promise for usage in Canada. This research quantifies the benefits of adopting new strategies into Ontario's transportation infrastructure practice as case studies are evaluated for their ability to mitigate the GHG emissions in the transportation sector.

Four strategies were selected and studied based on their feasibility in term of costs, level of adaptation and industry's existing capacity to practice in Ontario. The strategies are Moveable Barrier System, Accelerate construction, Two lift concrete pavement construction and High Modulus Asphalt pavement design Case studies focused on improving the traffic congestion, rapid construction practices, improved design standards, modified construction practices, reducing the consumption of virgin aggregates and allowing the use of more locally available material.

GHG emission results and associated impacts are calculated and compared between conventional methods and selected innovations to evaluate the feasibility of adopting the strategies for cost, internal resources and existing capacity in Ontario's industry. The Athena software tool was used to perform a life cycle analysis and the comparative studies between the conventional methods and new innovative strategies.

Overall the results using Athena software as well as manual calculations shows that selected new strategies helps to reduce the GHG emissions from the transportation construction practices.

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Dedication

This thesis is dedicated to my parents Balwinder S Dhaliwal and Amarjit K Dhaliwal and to my wife Ramneet K Dhaliwal, without whose love and support would never have been possible.

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Chapter 1-Introduction

1.1 Background

Among all the gases in the earth's atmosphere, Greenhouse Gases (GHG) act as an insulation for the earth, and they trap the heat in the earth's atmosphere. There are many factors which increases Greenhouse gases. The addition of Greenhouse gases has been initiated by various human activities, including emission of fuel from vehicles, production industries. Increased manufacturing and population growth around the world has resulted in an increase in greenhouse gases to the atmosphere. This has had a huge impact on our Earth's environment, making the planet warmer. Canada produced over 720 megatons (Mt) of greenhouse gases (GHG) in 2015[1].

Greenhouse gas emissions have initiated the interest of various research studies, including in the transportation and pavement industry. Road infrastructure plays a critical role in the economy, but also contributes to quality of life. Rapid growth in the transportation and infrastructure sector made the transportation industry the fastest growing source of Greenhouse Gas (GHG) Emissions [2]. Reducing greenhouse gas emission while constructing, maintaining and rehabilitating the road networks is beneficial for climate change, human health and road user cost. A good road network is one that provides an adequate level of service and achieves desired efficiencies[3]. However, the construction and maintenance of road networks have undeniable impacts on the environment and on the quality of life of human and other living beings[4][5].

In 2015, the transportation sector was shown to be the second largest contributor to Canada's total Greenhouse Gases (GHG) Emissions (Figure 1). There is no official data to calculate the GHG emissions solely related to how the pavement sector contributes to this number. However, the data from Environment Canada and Climate Change Canada [6] indicates more than 85% of emissions were related to on-road

vehicle operations (Figure 2) [6]. So, managing the GHG emissions from the road vehicle operations is the biggest challenge during the construction and maintenance activities. Managing traffic congestion and delays are main factors which contributes to GHG emissions. The design and surface characteristics can influence vehicle fuel efficiency, thus can increase the environmental impact caused by cars and truck fuel combustion by 10% [7].

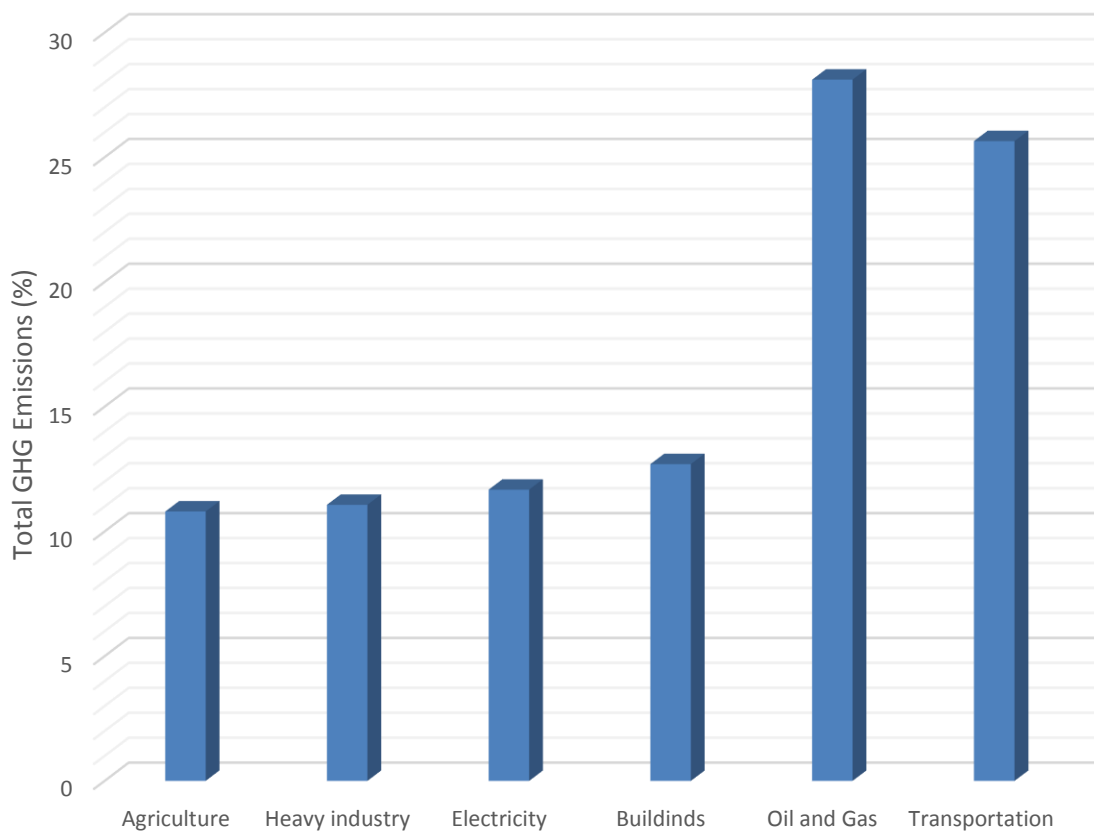


Figure 1-Total GHG Emissions By Canadian Economic Sector in 2017 [6]

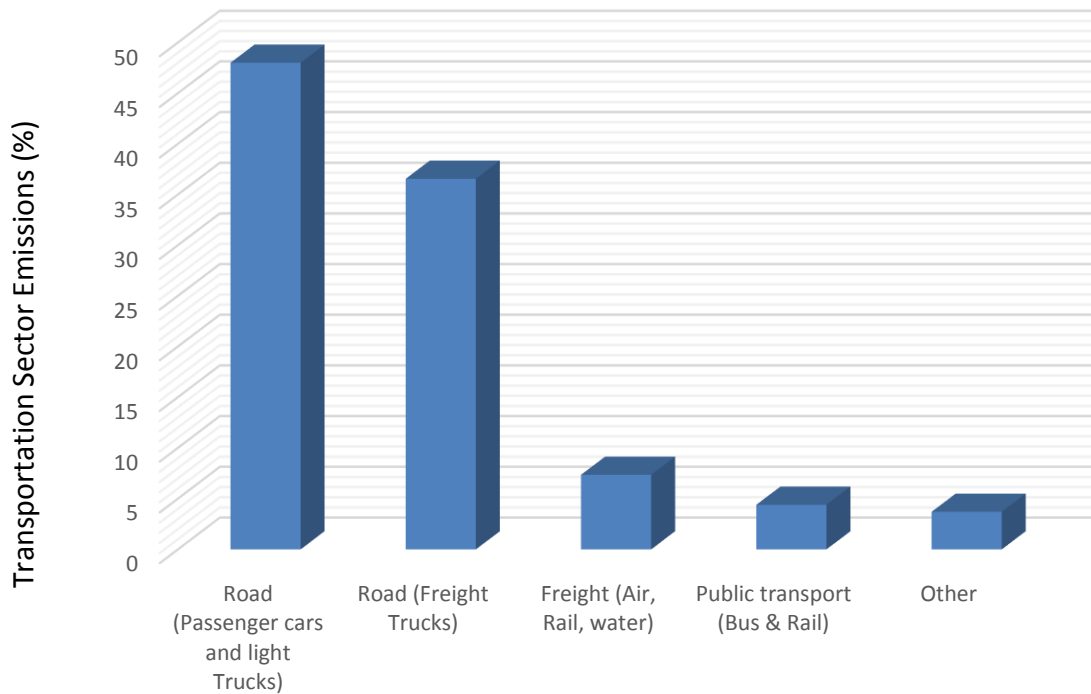


Figure 2-Breakdown in Transportation Sector by Intended Use. [6]

Greenhouse gas (GHG) emissions are the main concerns for all national and international agencies[8]. With the growing awareness of public regarding climate change and the need to take action to prevent it, an increasing number of worldwide agencies have started to integrate climate change considerations into their transportation system developments and operational activities[2].

The Government of Canada allocates over 25 billion dollars annually to pavement maintenance and capital projects [9] (as mentioned in the Government of Canada's Website, <https://www.tc.gc.ca/eng/policy/anre-menu-3037.htm>). Canadian

transportation agencies are facing very complex challenges in an effort to address deteriorating pavement conditions. Pavement managers are focusing on the technical aspects of the design strategies. This drives the allocation of resources and selecting maintenance policies for existing pavement conditions. By this the environmental criteria are always being overlooked during the decision making [8],[10].

Canada declared an aggressive goal of reducing GHG levels by 37% below the 1990 levels of GHG emissions by 2030 and 80% below by 2050 at the Conference of the Parties (COP) under the United Nations Framework Convention on Climate Change (UNFCCC) 2015 Paris Agreement[11]. Canadian transportation agencies are actively trying to mitigate the environmental impacts of transportation and road infrastructure. Ministry of Transportation Ontario (MTO) Road Talk magazine recommends that agencies should supports and seek the strategies to reduce the environmental impacts during the planning, design, construction, and maintenance phases of highway and transportation infrastructure [12].

Ontario is the second largest contributor of emissions among all the provinces in Canada (Figure 3) [13] and the transportation contributes more than 35 % of emissions in Ontario.

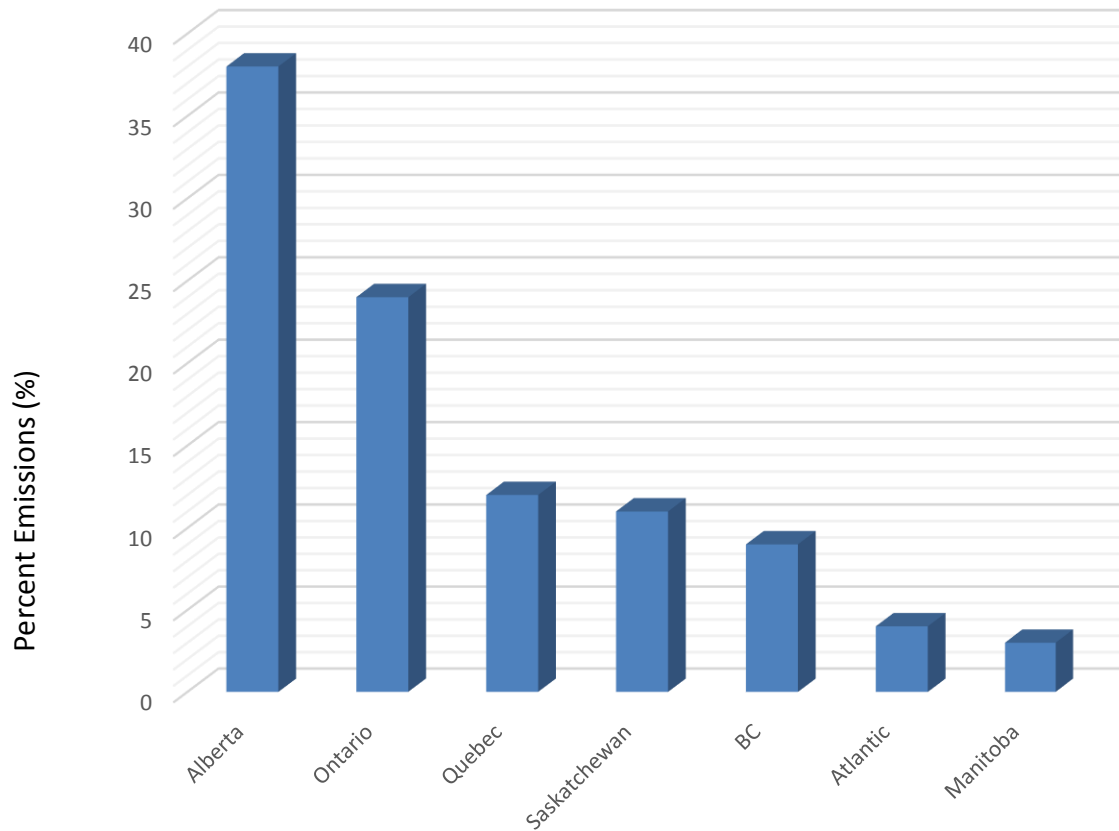


Figure 3-Emission by Canadian provinces (MTO Change Overview, 2018) [13]

In the transportation sector, road vehicle operations play a very crucial role in Greenhouse Gas (GHG) emissions. Emissions from the vehicle fuel consumption during construction, maintenance and service phase of road infrastructure results in an adverse impact on the environment. The industry needs to research new techniques and strategies to lower these impacts. During the decision-making process, the amount of emissions produced by vehicles in service, construction and

maintenance phases of the pavement lifecycle were never considered. These phases have a significant impact on the environment due to traffic delays, accidents and increased road user cost.

Innovations in the road construction sector is very beneficial, as it is certain to bring better results, such as better-performing roads with lower adverse environmental impacts, lowered costs and improved quality that would require low maintenance [14].

1.1.1 Problem Statement

Canada has extreme temperatures namely cold temperatures in the winter and warm temperatures in the summer. This environmental loading can pose a major challenge to roads as it contributes to deterioration. Truck transportation is also the dominant mode of transportation for goods and services in Canada. Thus the importance of road travel cannot be underestimated [14]. Canada faces many challenges in maintaining road transportation infrastructure as the roads are aging and there are limited funds available for maintenance and repairs. Traffic volumes and vehicle loads continue to increase, putting even more demand on the already stressed pavement system in major metropolitan areas, resulting in serious congestion problems [15]. These challenges force different jurisdictions to form innovative ways to sustain and develop new transportation infrastructure. As our highway infrastructure ages, the transportation industry needs to find alternatives or strategies of building, maintaining and reconstructing roads infrastructure that is cost effective and minimizes the environmental impacts.

The transportation sector needs a new approach in implementing sustainable pavement solutions to reduce the economic cost over the life cycle and increase the societal benefits[15]. This can be achieved by adopting different strategies in an effort to reduce greenhouse gas (GHG) emissions. Greenhouse gas (GHG) emissions can be reduced by different ways such as:

- Managing traffic congestion.
- Reducing congestion during the construction and maintenance phases of road infrastructure.
- Making the road infrastructure resilient to avoid or decrease the frequency of maintenance activities, which will lead to less congestion on the roads.
- Use of accelerated construction and maintenance strategies to reduce the road closure time.
- Awarding contractor for reducing construction time and congestion.
- By incorporating the strategies to evaluate the greenhouse gas (GHG) emission at the contract completion stage.

1.2 Research Objective and Scope

There is a need in Canada for supportive sustainable transportation strategies to mitigate GHG emissions. Many countries such as America, Australia, European countries, have experience in advancing new technologies for reducing the emissions, thereby acting as a guide for Canada to implement or innovate such strategies. The aim of this research is to identify strategies that are currently used in the road construction industry by different jurisdictions which may show promise for usage in Canada. The objectives and scope of this research include:

1. To study strategies which reduce GHG emissions in the road construction sector by different jurisdictions around the world. This study will collect the data regarding the technology and equipment used. It will characterize and compare strategies in cost comparison for adopting mitigation options.
2. To evaluation the feasibility of adopting strategies in Ontario's construction practices.
3. To establish framework and guideline for implementation in Ontario.

1.3 Research Organization

This research thesis is organized into the following tasks (Figure 4) and chapters as stated below.

- Task 1 - Review GHG mitigation measures from different jurisdictions.
- Task 2 - Analyse strategies and implementation practices as case studies for different innovations.
- Task 3 - Determine the factors and the drivers that lead to the acceptance and implementation of innovation in the road construction industry.
- Task 4 - Evaluate the feasibility of adopting measures into practice in Ontario.
- Task 5 - Establish framework and guideline for implementation in Ontario.
- Task 6 - Conclusion and recommendation will be provided for the acceptance.

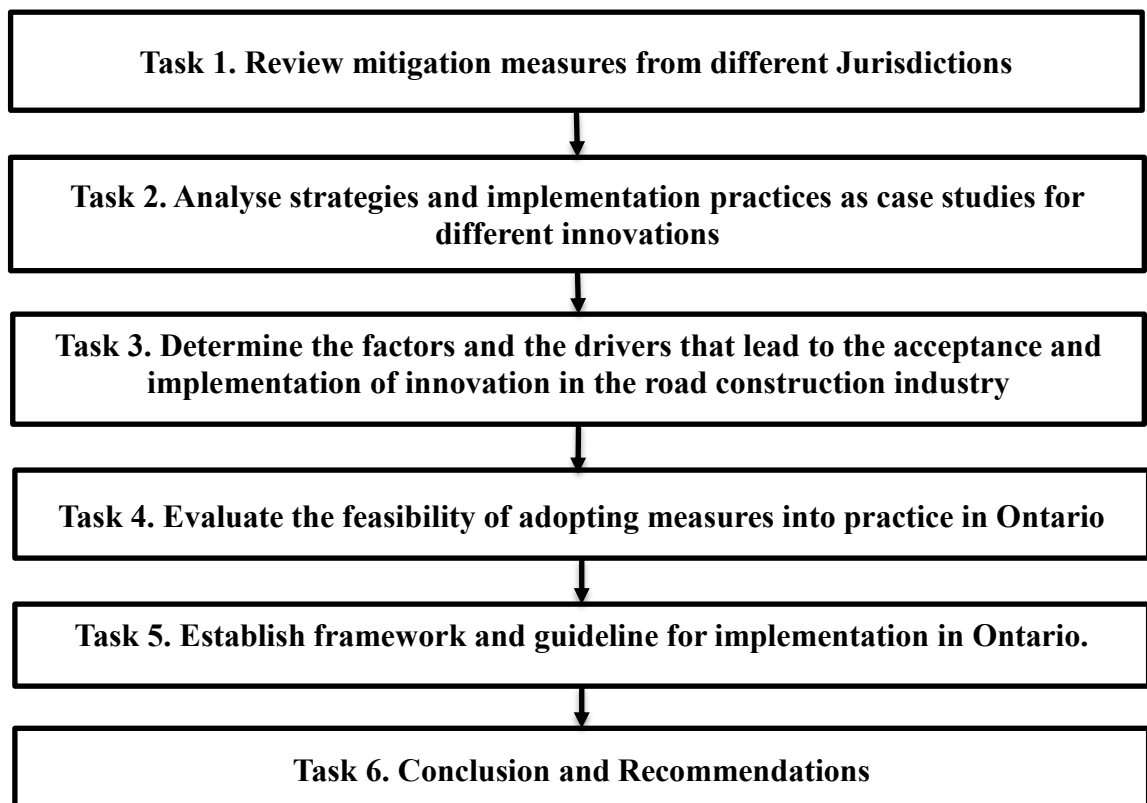


Figure 4-Research Organization Task Diagram.

The content of each chapter in this thesis is described below:

Chapter 1: Introduction - It includes the needs of GHG mitigation strategies in the transportation construction practices, followed by the objectives and scope of the research thesis.

Chapter 2: Literature Review – This chapter includes a comprehensive review of highway management practices and strategies, their needs and requirements. Also includes the list of innovative strategies and case studies.

Chapter 3: Research Methodology – This chapter includes introduction for all the case studies used by different jurisdictions for GHG mitigation strategies with analysis and summary of findings.

Chapter 4: GHG Emission results and Associated Impacts – This chapter includes the comparison of existing capacity of Ontario's construction industry and industries response on the adaptation of new innovative techniques in Ontario's construction practice.

Chapter 5: Conclusion – This chapter includes the recommendations based on evaluation and feasibility comparison of Ontario's existing capacity and industrial partner's response.

Chapter 2- Literature Review

2.1 Highway Management Practices and Strategies

The study of environmental impacts from different road construction and management methods and techniques used in the transportation industry is important for understanding their impact and how these impacts can be potentially reduced overtime. Transportation infrastructure has a direct relation to GHG emissions and society. It is the industry's responsibility to develop or adopt different practices and strategies to meet the demands of climatic changes to make the transportation infrastructure sustainable and environmentally friendly. There is a need for changing the existing highway management practices in planning, construction, maintaining and operational phases of the infrastructure.

As mentioned earlier, the transportation industry was the largest contributor to GHG emissions in Canada. The on-road vehicle operations contributed to more than 85% of GHG Emissions[6]. Inefficient highway management strategies and surface characteristics can lead to higher vehicle fuel consumption which can impact the environment by more than 10% [7].

Two lane highways with asphalt pavement will need almost 25000 tons of material for the construction of a one-kilometer section of road [14]. All construction materials are produced from the mining distillation activities. The transportation of raw and processed materials to the construction sites also consumes a very high percentage of fuel, which makes the transportation industry one of the biggest contributors to global climate change. There is pressure on the transportation industry to bring the changes into the highway management practices and strategies to reduce the environmental impact from the construction, maintenance and operational phases. The Ministry of Transportation Ontario (MTO) is taking the initiative to develop the GHG mitigation strategies for the transportation industry in Ontario.

Growth in population and industrialization increased the traffic volume, size and the axle loads on the roads at a very fast rate. It all leads to the damage of the road infrastructure and an increase in congestion, air and noise pollution. The industry needs to initiate or adopt different practices and strategies to make the road's infrastructure sustainable. Incorporating and adopting the new techniques and strategies related to the latest technologies, materials, and processes in the construction of roads will enhance the efficiency and improve the overall quality of the infrastructure.

There is a growing need to find durable as well as reliable strategies for constructing and maintaining resilient roads that are economical. Innovations will reduce the maintenance costs of the road construction sector [14] and make our system sustainable to meet future needs by reducing any adverse effects on the environment. Canadian transportation authorities are under pressure to reduce the emissions caused by road construction projects in order to meet the emission targets declared by Canadian Government[11]. The government requires the involvement from the transportation authorities to develop the GHG mitigation strategies to reduce the emissions.

This is because of the following factors:

- Transportation sector is the largest contributor to greenhouse gases emission.
- Transportation sector needs to mitigate the GHG emissions at the minimal cost by adopting the new technology and innovation used by the other jurisdictions.

Due to global warming and changes in the environment, challenges for the transportation sector in construction, maintenance and operations are going to increase. There is a need for adopting new strategies to overcome the above-mentioned issues in the development of transportation infrastructure. New methods will make our system better equipped to deal with the future needs of environment changes.

The governments of Queensland and Western Territory in Australia showed concern about the need for adopting sustainable strategies to mitigate the greenhouse gases and reduce the costs of road construction and maintenance [14].

The government of Manitoba also updated their Environment Act to incorporate and implement the new technologies to mitigate the GHG emissions[16]. The implementation of advanced technologies and innovations will provide better outcomes and improve the quality of roads and their construction methods. New technologies or strategies will also bring improved management in the transportation industry, which is essential for the quality and for delivering the value for money to its end users.

2.2 Need of GHG Mitigation Strategies

Innovation is the act or process of introducing a new idea, devices and methods in order to further satisfy the needs of its end users [17]. It is a way of doing new things or finding improved and new ways of doing conventional things. Innovations can be incorporated at any phase of the transportation sector. It has always been a very crucial part in the development and growth of the construction industry [14][18]. The main scope of this thesis is to research various innovative strategies for design, construction and operational phases to mitigate the GHG emissions related to pavement activities. The transportation sector needs to involve innovative strategies in planning and research in order to bring innovation in a proper way [19].

New technologies or strategies will make our road infrastructure more sustainable and resilient that would require less maintenance with less adverse impacts on the environment. A feasibility study is then carried out where the strategies are applied to the province of Ontario's Highway Management System to examine the performance. Roads constructed and maintained by using the innovative strategies are always directed at improving the environment and user-friendly treatments that results in lowering the maintenance costs. Innovations are only deemed to be acceptable if it brings benefits to society and to the environment.

A study was conducted at the University of Queensland in Australia that used the innovative strategies in transportation construction industry to increase the efficiency, number of clients, cost-effectiveness and technical performance of the pavement infrastructure. It also makes the system more accurate, informative and knowledgeable to develop better roads, as shown in Figure 5. X-axis of the graph represents numbers to show the corresponding increase of factors by incorporating the innovative strategies. To fulfill the present needs, it is not always necessary to develop new ideas as often lessons learned from other jurisdictions can be applied. These innovative ideas or strategies can be adopted from other jurisdictions. This research reviews the strategies and examples, if they can be applied to Ontario's pavements construction practice.

It is a complex process to design and successfully construct a road, maintain and rehabilitate it while having minimal environmental impact. Fuel consumption from the daily traffic from cars and heavy trucks are the bigger factor of environmental impacts. Several research papers has shown that durability and sustainability of the transportation sector are directly related to each other. Thus, durable infrastructure requires less maintenance and avoids the user delays associated with the congestion on the roads [20].

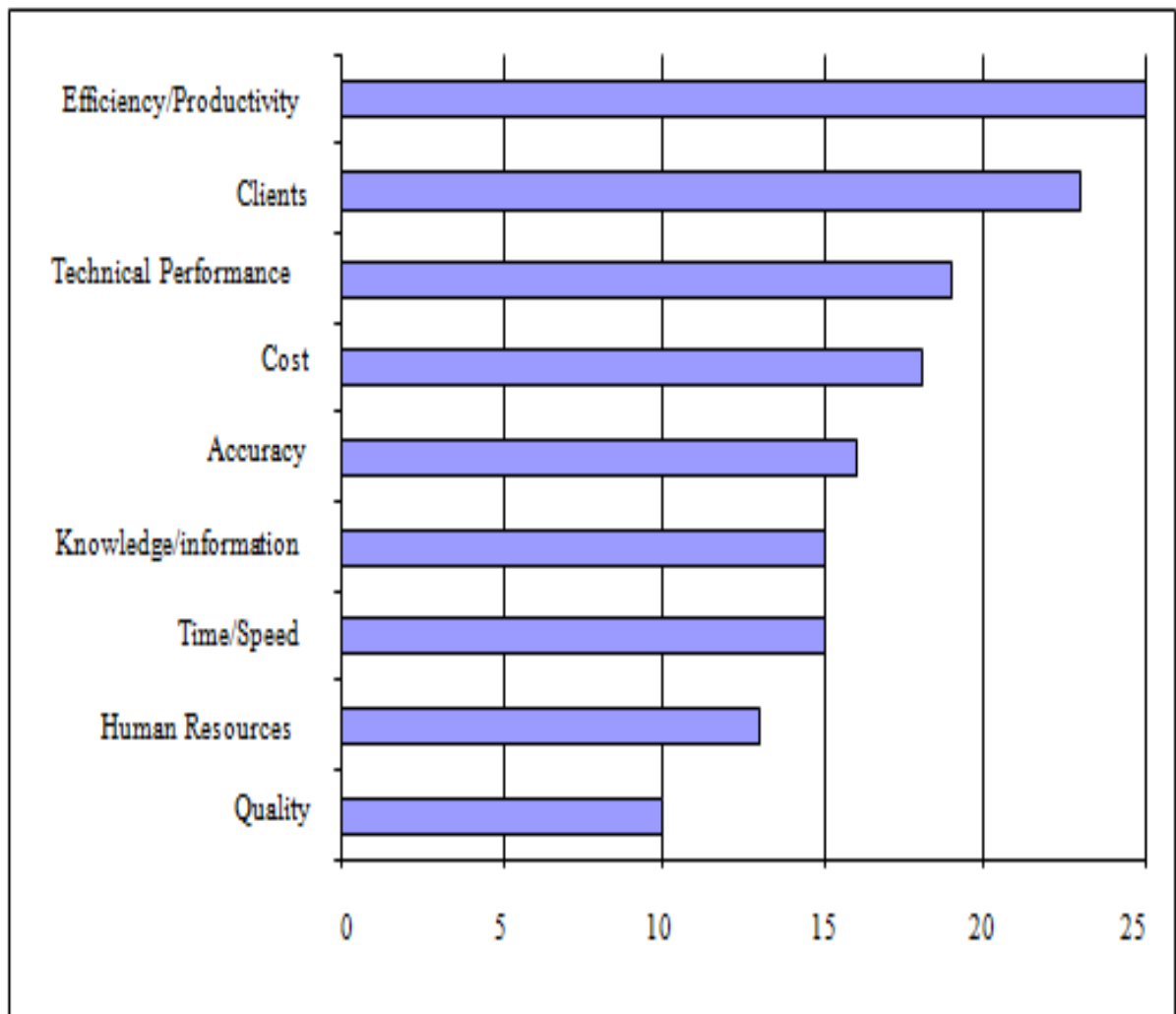


Figure 5-Innovative Practices in Queensland Road Authority (Austroads, 2014)[14]

Studies completed in Europe by the European Commission, factors like rush hours, weather conditions, accidents, lane closures for road constructions and maintenances activities are the main reasons for congestion on roads. Traffic queues and delays during these three phases (construction, maintenance and operations) impact the environment by increase in vehicle fuel consumption. Due to the extra fuel consumption and related air emissions, traffic congestions become a noticeable element for the road life cycle. In order to reduce the environmental impacts, effective

traffic management practices and strategies are needed for accommodating the future needs.

For incorporation of climate change studies, the Ministry of Transportation Ontario (MTO) published a Value Engineering Report for Provincial Highways Management Practices. MTO identified 21 initiatives to consider and implement in Ontario's transportation practices [21]. This shows the clear intentions of MTO to incorporate the new climate change studies for the GHG mitigation opportunities. Value Engineering (VE) team was provided with Functional Analysis and Preliminary Function Analysis System Technique (FAST) diagram shown in Figure 6.

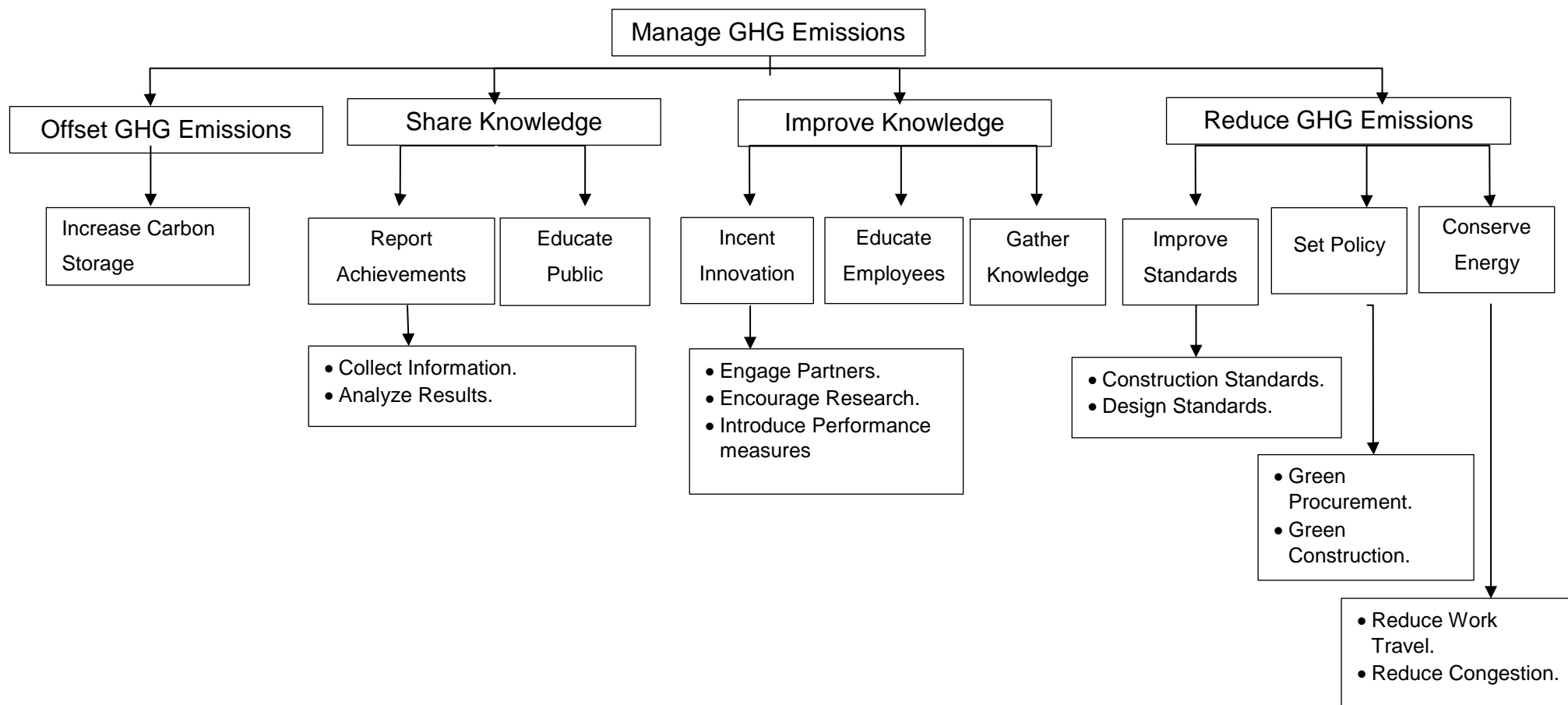


Figure 6-FAST Diagram from Climate Change VE Study [21]

The intention of this thesis is to identify the strategies targeting one of the major functions, for example reducing GHG emissions as described in the FAST diagram.

The innovation process for this thesis comprises of following steps:

- Identify innovative mitigation strategies from different jurisdictions.
- Analyze strategies and implementation practice.
- Evaluating feasibility of adopting strategies into practice in Ontario.
- Conduct a case study which includes adaptation of strategies to Ontario.

2.3 List of the Innovative Strategies/ Case Studies

The following strategies have been selected and will be evaluated based on their feasibility on the costs, level of adaptation and industry's existing capacity to practice in Ontario. The selected case studies are:

1. High Modulus Asphalt (EME2) pavement design.
2. Two lift concrete pavement construction.
3. Accelerated (24x7) Construction.
4. Moveable Barrier System.

The goal of this research work is to investigate and evaluate the feasibility of implementing innovative GHG mitigation strategies in the highway design, construction and maintenance from different jurisdictions with the help of different case studies. Strategies will focus on the following points:

- Improving the traffic congestion during the construction, maintenance and operational phases of the road.
- To accelerate the construction and maintenance phases to reduce environmental impacts.

- To improve the design and durability of our road infrastructure to reduce the maintenance activities.
- Study the alternative techniques to reduce the consumption of virgin aggregates and reusing the recycled material in transportation infrastructure.
- Innovations to use as much as locally available material to reduce the haul of virgin material from far distances.

Chapter 3– Research Methodology

3.1 Introduction

A few case studies have been taken into consideration which provide techniques/strategies to evaluate the feasibility of applying them in the Ontario's construction industry. These case studies are focused on mitigating the GHG emissions by using the improved practices to reduce pavement thickness to consume less virgin/premium aggregates and incorporate locally available materials without compromising the life and structural capacity of the infrastructure. Some strategies like accelerated construction practices, helps to reduce congestion queue. The research also aims to identify improved design strategies to increase the life of the infrastructure and cut down the frequency of rehabilitation and maintenance activities.

The scope of the present research is to quantify the benefits of adopting new strategies into Ontario's transportation infrastructure practice as these case studies are evaluated and adopted by the other developed jurisdictions to mitigate the GHG emissions in the transportation sector. The selected case studies provide a complete understanding different scenarios to gain the benefits of resilient infrastructure. Which need few maintenance throughout the serviceability life. It leads to less disruption on the roads and reduces GHG emissions. The case study research method also provides an opportunity to compare and evaluate more information instead of single source of data. It also provides the ability to compare the potential benefits and limitations of the strategies from the practical experience.

Selected case studies will focus on reducing the GHG emissions as described in FAST diagram as noted in Figure 6 Chapter 2, in MTO's climate change VE report. Case studies will also provide valuable inputs to functions identified by the facilitators such as

1. Improve/Modify the existing standards.
2. Conserve energy.

As explained in the FAST diagram, to achieve the improved standards there is a need to modify Ontario's design and construction standards. Similarly, the strategies to

reduce work travel and congestion will help conserve energy. Saving in energy can be achievable by improving technologies, manage scheduling, group commuters and accelerated construction techniques.

All the case studies will impact these ideas and will be discussed in more details in the following chapters.

3.2 Analysis of Case Studies

3.2.1 Case Study I - High Modulus Asphalt Design

High Modulus Asphalt (EME2) (University of Stellenbosch Study)

The goal of effective pavement design includes building long-lasting pavements to reduce the life cycle cost, frequent maintenance and rehabilitation so as to meet the growing traffic volume and axle load demand. If successfully executed it will result in reducing GHG emissions during construction, but also throughout the entire life cycle. High modulus asphalt is also known as EME (Enrobés à Module Elevé) developed in France in 1970s. EME is the abbreviation of French name “*Enrobés à Module Elevé*”, which means “asphalt with an elevated modulus,” or simply “high modulus asphalt.”

EME asphalt is suitable for heavy traffic and high-volume pavements such as runways, taxiways, aprons, slow speed lanes/stretch and bus lane. EME also helps to meet the thickness constraints in urban areas without compromising the load carrying capacity of the mix. EME has a high resistance to the permanent deformations as well as stiffness as compared to the conventional asphalt mixes for base course. Due to the higher asphalt content, EME has better fatigue resistance than the normal asphalt mixes.

Benefits - EME mixes have very high stiffness and shear strength properties. This helps to distribute the wheel loading at the wider angle and improve the integrity of the bottom layers. Wheel load distribution is better with EME mixes than traditional asphalt mixes as shown in Figure 7 and Figure 8 [22]. EME mixes possess higher stiffness

and shear strength as compared to traditional asphalt mixes. High stiffness and shear strength help to disperse the stress in pavement more than in normal asphalt mixes.

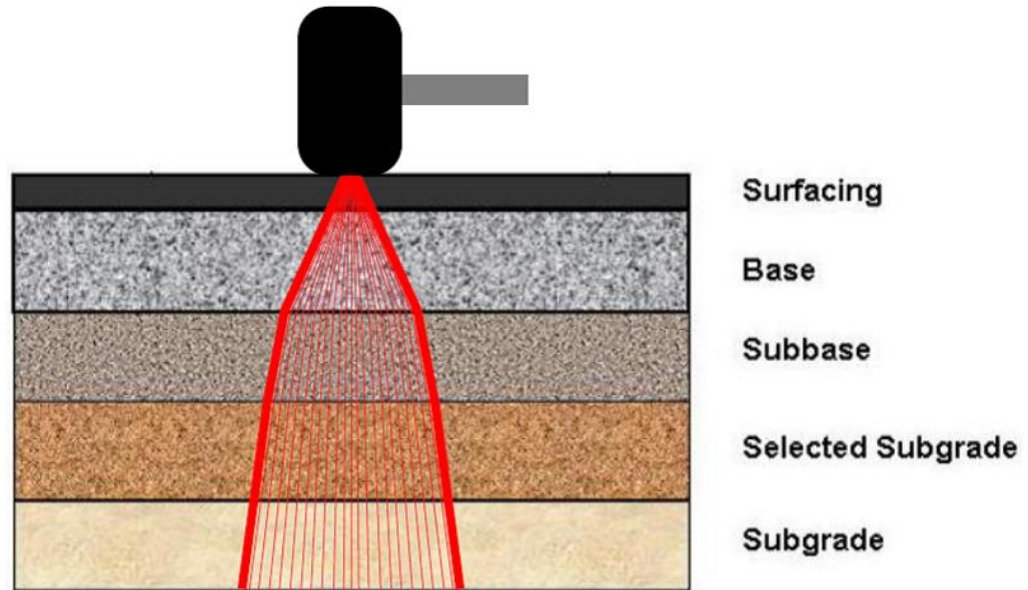


Figure 7-Typical Stress Distribution in HMA Pavements[22]

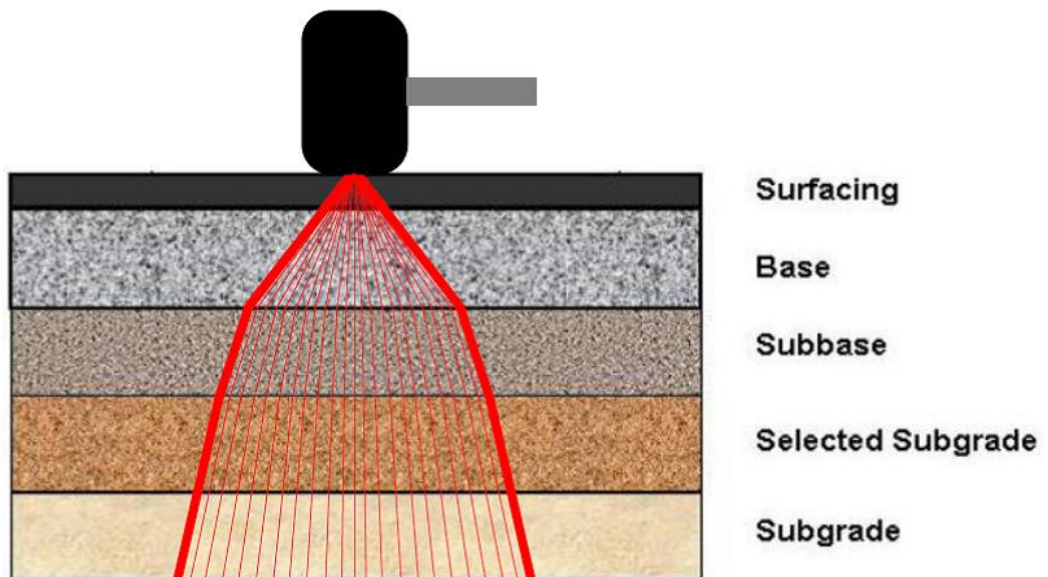


Figure 8-Typical Stress Distribution in EME (High Modulus Asphalt) [22]

EME asphalt can be considered as a sustainable option due to the following reasons:

1. EME helps to reduce the thickness of the asphalt layers, without compromising the structural strength requirements for the pavement. Reduced pavement thickness reduces the volume of material required for construction. Less material demand will cut the GHG emissions to the environment as well.
2. Studies show that EME is a cost-effective solution based on the overall life-cycle costs analysis.
3. EME also helps to reduce the road user delay costs.
4. EME mixes improve the pavement durability.

Many countries such as France, Australia, South Africa and the United Kingdom are implementing high modulus asphalt. France developed this technique originally in the 1970s. This mix was developed to provide adequate resistance to fatigue and permanent deformation in the pavement structure by reducing the thickness needed for the pavements. It is very difficult to design a mix to meet both rut resistance (permanent deformation) and fatigue resistance. They are major contributors to the pavement failures in the present time. Due to the higher PGAC content and stiffness modulus, EME mixes perform well against rutting and fatigue deformations. EME mixes also possess good ability to resist the moisture susceptibility in the pavement structure, which also contributes to the long life of the pavement infrastructure. In earlier years European countries were using EME as a base layer, which was designed against the fatigue only and top layer mix was used and designed for the rut resistance (permanent deformation). EME mixes are designed as an impermeable mix and at higher mixing temperature.

This mix is classified EME class 2 as per France mix design methodology which is used for high traffic volume roads. Typically, EME mixes are designed with following parameters

1. Higher binder content, around 6 % by mass of aggregates.
2. Stiffer binder (Pen Grade 10-25, PGAC 88-16).
3. With lower air voids content.
4. High Modulus > 14 Gpa at 15°C and 10 Hz.

A study done in Australia under National Assets Centre of Excellence (NACOE) for implementation of high modulus asphalt shows that the EME mixes are able to reduce the pavement costs, with an increase in pavement life. With the use of EME mixes, the frequency of pavement rehabilitation and maintenance periods will be reduced. EME mixes are the best solution to provide fatigue and rut resistant mixes by keeping the lift thickness low to meet the constraints of the urban environment. The study also shows that with the use of EME mixes it will be able to reduce the overall thickness of road structure by 15-20 % without compromising the structural load carrying capacity of the road, as shown in Figure 9.

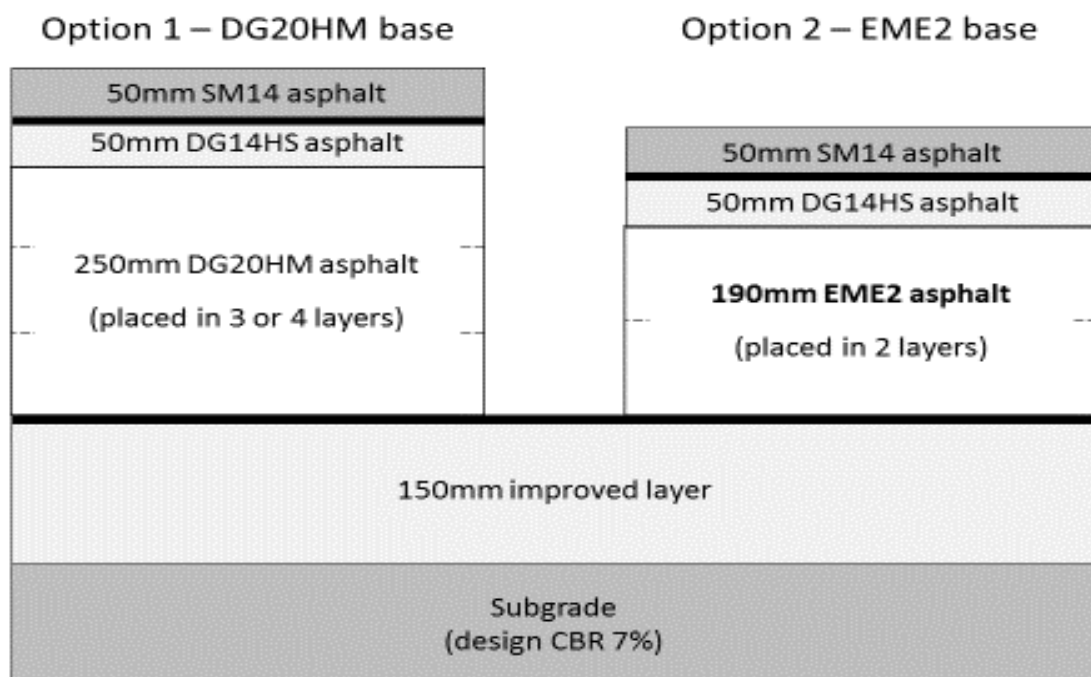


Figure 9-Design Thickness Comparison between EME2 and Traditional Pavements (NACOE)

NCAT Study

A study was completed by NCAT for the High-Modulus Asphalt Concrete (HMAC) 2017 to evaluate performance testing compared to the existing state-of-the-practice on HMA mixes. Following mixes with different material and binders, were tested under this program:

1. French mixture with a binder (PG 88-16).
2. Mix with 35% Reclaimed Asphalt Pavement (RAP) with the polymer-modified binder.
3. Mix with 35% Reclaimed Asphalt Pavement (RAP) with higher polymer content.
4. Mix with 25% Reclaimed Asphalt Pavement (RAP) and 5% RAS with a polymer-modified binder.
5. Mix with 50% Reclaimed Asphalt Pavement (RAP) with a polymer-modified binder.

A systematic laboratory testing program was done to estimate the fatigue cracking, permanent deformation, stiffness properties at different temperatures and binder performance.

AASHTOWare Pavement ME Design software was also used to determine the effect of a high-modulus base on asphalt pavements performance.

Results from the study indicate that the [23]

- RAP helps to stiffen the asphalt mix sufficiently for high-modulus asphalt mixtures. The higher percentage of RAP can be used in HMAC mixes.
- HMAC mixes also showed higher flow number test results compare to the conventional HMA mixes.
- Results indicate that HMAC has higher stiffness values which will lead to the improved performance of asphalt pavements in fatigue cracking, ride quality and rutting as opposed to normal HMA mixes.

- AMPT test results has shown improved fatigue properties for the high polymer modified mixes.

The study approved the European mix design standard methods and specifications to be used in the North American practice and can be implemented on local virgin and recycled materials.

3.2.2 Summary of Findings of High Modulus Asphalt

- Long lasting pavements with reduced life cycle cost.
- Suitable for high volume roads.
- Saves virgin material due to reduced design thickness.
- High resistance to permanent deformation and better fatigue resistance.
- Accommodate higher reclaimed asphalt pavement material due to modified design requirement.
- Improved pavement durability.

3.2.3 Case Study II – Two Lift Concrete Pavement (2LCP)

Two-Lift Concrete Paving is also called 2LCP. It involves placing two layers of concrete (fresh-on-fresh or wet-on-wet) in place of a single layer of concrete [24]. With 2LCP technique, this results in reduction in the quality of concrete for the bottom lift, without compromising the overall performance requirements of the pavement. Thus, the bottom lift will never be exposed to direct traffic and environment. Typically, the bottom lift covers 80 to 90 % of the total pavement thickness and it contains locally available aggregates as opposed to the aggregates used in a traditional paving project. This helps to reduce the GHG emissions and harmful effects to the environment, by reducing the number of trips to haul the premium quality material from quarry to site.

This strategy provides excellent options to the owner body to construct a sustainable pavement with reductions in GHG gases. The 2LCP model provides the opportunity of:

1. Using the locally available aggregates in the bottom layer.
2. Using the material which may not be suitable for traditional one lift concrete pavement.
3. Use of recycled materials in large quantities.
4. Provides the opportunity to use higher levels of Supplemental Cementitious Materials (SCMs) in bottom layer of concrete pavement.
5. Provides the opportunity to the designer to optimize the mix for top layer to improve the desired properties, skid resistance and noise reduction.

Two-lift concrete paving (2LCP) is a sustainable alternative to the single lift concrete pavements. This helps to reduce GHG emissions by allowing the use of locally available and recycled aggregates and cut down the emissions produced from the transportation of these aggregates, 2LCP allows the designers to use more SCM material which again cuts down the GHG emissions from the production of cement process.

A typical 2LCP pavement section is shown in Figure 10. Bottom layer in 2LCP is thicker and usually consists of locally available aggregates with a higher percent of RCMs (Recycled concrete material) and SCMs. On the other hand, the top layer is thin and designed with high-quality materials to provide better skid resistance and durable pavement.

Using 2LCP as an alternative will allow more economical and sustainable concrete mixtures to be used for the bottom layer by permitting significant amounts of locally available materials, which may not be suitable for surface courses, such as recycled aggregates (recycled concrete aggregate (RCA) and reclaimed asphalt pavement (RAP) and also using the lower percentage of cement contents in the bottom layer. It will provide more flexibility to the designers for efficient and economical use of premium mixtures to maintain the anticipated surface characteristics for top layers of concrete pavement.



Figure 10-Typical Two Lift Concrete Pavement Construction. (2LCP) [24]

It should be noted that this technique has some challenges and concerns due to the limited number of projects completed in the past. Industry had not enough experience and data regarding the implementation of 2LCP technique into practices. Some challenges and concerns have been identified with the implementation of 2LCP technique. They are as follows:

1. This technique will impact the schedules and time lines for the projects, as industry is not experienced to handle the projects with 2LCP.
2. No experience of designing the right mix proportions to meet the structural requirements of 2LCP pavement.
3. 2LCP technique will incur extra cost to the project for additional equipment, quality control testing and more labour requirements.
4. Need more on site supervision and control to assure the quality of 2LCP product.

Though this is not the new technique for the world, some European countries like Austria, Belgium, Germany, and the Netherlands are using this techniques. The 2LCP technique was also highlighted in the Federal Highway Administration's (FHWA) Highways for LIFE program and Office of Pavement Technology [25].

Since last 20-30 years some US state DOTs have conducted some experiments on 2LCP construction techniques to improve the surface properties and increase the incorporation of recycled material in highway road construction. Projects constructed in Florida, Iowa, Kansas, Michigan and North Dakota from 1970 to 1994 are still in good serviceability condition. Some recently constructed projects are part of this study. Table 1 below shows different parameters for the projects complete in the past.

Table 1-List of Projects used 2LCP in United States of America.

Year	Location	2LCP Section details	Standard. Section	Material used	Conclusion	Construction constraints	Total Cost \$(per SY) Conventional/ 2LCP
1993	I-75 Detroit, Michigan	10 inch, (7.5 inch bottom,2.5 inch Top)	11 inch Joint- Reinforced Concrete	Same Aggregate and Cement	LCCA showed that 2LCP will be economical if the initial cost does not exceed by more than 17 %	Less industrial experience , Small section projects hard to manage	37.58/ 87.76
2008	I-70 Kansas	11.8inch Bottom, 1.6 inch Top lift		Porous Limestone (Bottom lift), Rhyolite aggregate with 20 % Fly ash(top lift	2LCP was found to be a very practical approach,	Managing the different mix delivery to the site, which was sorted out with colour coding to differentiate the mixes.	48/41

2010	I-94 Minnesota	6inch Bottom lift,2 Inch Top lift		High Quality EAC top lift with 15 % Fly Ash, Low cost bottom Lift with 60 % fly ash		Management issue to schedule the mixes and construction properly	20.38/19.94
2010	I-94 Minnesota			Has additional 50% RCA replacement was in bottom lift.			
2012	Illinois Tollway			15to 50 % FRAP(fractio nates recycled asphalt) and 35-50 % SCM was used in bottom lift	Meets the Illinois DOT strength requirement. Mix has higher fracture energy than virgin concrete		65/45.92

The Kansas I-70 projects (2008) with the Life Cycle Analysis (LCA) showed 15% reduction of global warming potential as compared to traditional single lift concrete paving [34].

Performance evaluation of 2LCP pavement on Florida's US-41 was done in 2007 after 30 years of its construction. Almost 6.2 million Equivalent Single Axle Loads (ESALs) traffic loads were subjected on this highway before the evaluation. It was determined that most of the sections were in good service condition. Performance evaluation measurements were done for joints, pavement smoothness, load transfer, pavement deflection, and pavement cracking. [35].

European studies also indicate that 2LCP has a lower life cycle cost in comparison with an equivalent single lift pavements due to better structural strength, reduced maintenance and rehabilitation, better durability, improved ride quality and improved skid resistance.

Other Innovative Techniques

A project completed in Missouri in 2011 on HW-141 used photocatalytic materials in the top layer. Photo-chemically-active titanium dioxide (TiO₂) is mixed with the cement for top layer. This chemical is capable to reducing environmental pollutants from vehicle exhausts [36]. These kinds of opportunities introduce new innovations which are only possible due to small quantity of top layer mix that gives designers a flexibility to optimize the proportions.

3.2.4 Summary of Findings of Two Lift Concrete Pavement (2LCP)

- Accommodate recycled concrete aggregates in the bottom lift.
- Save the usage of virgin and premium aggregates by 70-80%.
- Reduce consumption of Portland cement.
- Lower life cycle cost.

3.2.5 Case Study III – Accelerated Construction (24 X 7).

I-15 California Devore Experience (2007)

Caltrans's (California Department of Transportation) completed the first large-scale project under the implementation of (Long-Life Pavement Rehabilitation Strategies) LLPRS program. Caltrans also finished I-10 Pomona concrete construction and I-710 Long Beach Asphalt Paving before this project. Caltrans's main goal was to implement new techniques/lessons learned from I-10 and I-710 demonstration projects to I-15 project.

This project was completed in two 9-day continuous (24 X 7) closures lasting approximately 210 hours in each direction with minimal interruption to traffic, which was originally estimated for 10 months of construction using traditional night-time closures. This project is also called Rapid Rehab. This project used innovative technologies to accelerate construction and mitigate traffic disruptions. With innovative technologies, they were able to reduce the traffic delays during regular and maximum peak-hour time by 50%. This directly benefited to reduce 28% of agency cost and 29% of road user cost there by reducing the travel time and congestion time during construction periods, which is the main contributor to GHG emissions as per the MTO 2016 report. [26]

California department of transportation used multiple approaches to complete the job in two 9-days continuous (24 X 7) operations. The techniques used were

1. Automates Work Zone Information System (AWIS) - for real time traffic updates.
2. Quickchange Moveable Barrier (QMB) system-to minimise traffic disruption and delays during construction.
3. Mix design of Rapid Strength Concrete (RSC) - for quick opening of road.

4. Web-Based Information System- for public surveys and publishing project updates.
5. Incentive/Disincentive Provisions – to encourage the contractors to meet the deadlines.
6. Multifaceted Outreach Program – to achieve public support.

The main goal of the study was to use innovative technologies and strategies to show:

1. Accelerate the construction process and schedule.
2. Mitigate traffic disruptions and measure its performance.
3. Achieve more traffic diversions by providing road users with automated real-time travel information.
4. Publish project information to the public through multifaceted outreach programs.
5. Capture change in public perception through the use of web-based surveys.

Project Details

The I-15 Devore project was total reconstruction of 4.5-Km mainline paving of two truck lanes from 20 Km north of the I-15/I-10 junction to south of the I-15/I-215 junction near San Bernardino, Figure 11.



Figure 11-I 15 Devore Project details [27]

The I-15 freeway carries an Annual Daily Traffic (ADT) of approximately 110,000 vehicles, with a weekday's rush hour volume of 5,500 vehicles in each direction with 10% of truck traffic. The I-15 is an important route for transporting goods across the state and accommodates higher leisure traffic volume on weekends going toward Las Vegas and resort locations along the Colorado river (on Fridays) and coming back (on Sundays).

The existing pavement was designed and built in 1970 with the cross section of 210-230 mm un-doweled plain jointed concrete over the 100-150 mm of cement treated base. Present scope was to reconstruct damaged concrete pavement with a new cross section of 290-mm doweled slabs using rapid strength concrete and a 150-mm asphalt concrete base on top of existing aggregate base. This scope also includes resurfacing of shoulders and reconstruction of wider truck-lane pavement than existing pavement to reduce the edge loading.

Evaluation of Rehabilitation Alternatives

Caltrans adopted a combined approach for preconstruction analysis, by selecting the most economical reconstruction closure scenario for construction schedule to minimise traffic inconvenience and agency cost. Following four scenarios were compared and evaluated with help of construction analysis for pavement rehabilitation strategies (CA4PRS) software of for above mentioned perspectives.

- 72-h weekday,
- 55-h weekend,
- one-roadbed 24-h/7-day continuous,
- 10-h night-time

One-roadbed continuous closure was evaluated as the most economical scenario, compared to traditional 10-h night-time closures. This scenario will need 80% less closure time which helps to reduce road user cost by 29% and agency cost by 28% for construction and traffic control.

Innovations Produce Significant Benefits

I-15 Devore project was done by Caltrans as “Rapid Rehab” reconstruction process to formulate accelerated construction techniques. It optimizes the construction schedules to minimize peak-hour delays. Other benefits from this project were:

1. Accelerated construction to finish the project in 3 weeks against 10 months for the traditional scheduling methods.
2. Minimal traffic congestions and less disruptions to commuters.
3. Long-lasting pavement design to increase the pavement life expectancy to 30 years from an original average life 15 years.
4. Introducing the QMB (Quick moveable barriers) to improve the safety for workers and public during construction period.
5. Reduced overall construction costs.

As per the preconstruction analysis accelerated construction helped to reduce the agency cost by 28% (\$6 million) and also the road user cost by 29% (\$2 million) by saving travel time. Though there was an increase in the direct cost because of the incorporation of new techniques, the study showed that the additional coats were worth the road user's costs and greatly improved public perception for innovations/ strategies used in Rapid Rehab Project.

Mitigated Traffic Disruption

A traffic research team collected the data for traffic volumes and speeds, before and during construction period. It showed an acceptable impact of reconstruction closures schedules on traffic. A web-based survey was also completed prior to construction and during construction to receive feedback from the public about the effectiveness of the techniques and strategies used to finish the project. The results revealed a change in public perception about the accelerated construction approach, Results are shown in the Figure 12.

There was approximately a 20 % reduction observed in traffic volume/ congestion, which was even 10 % more than the expected during the initial traffic management plan. Overall there was a reduction of 16 % traffic volume on north bound lanes and a 19 % reduction on the south bound lanes in daily traffic demand.

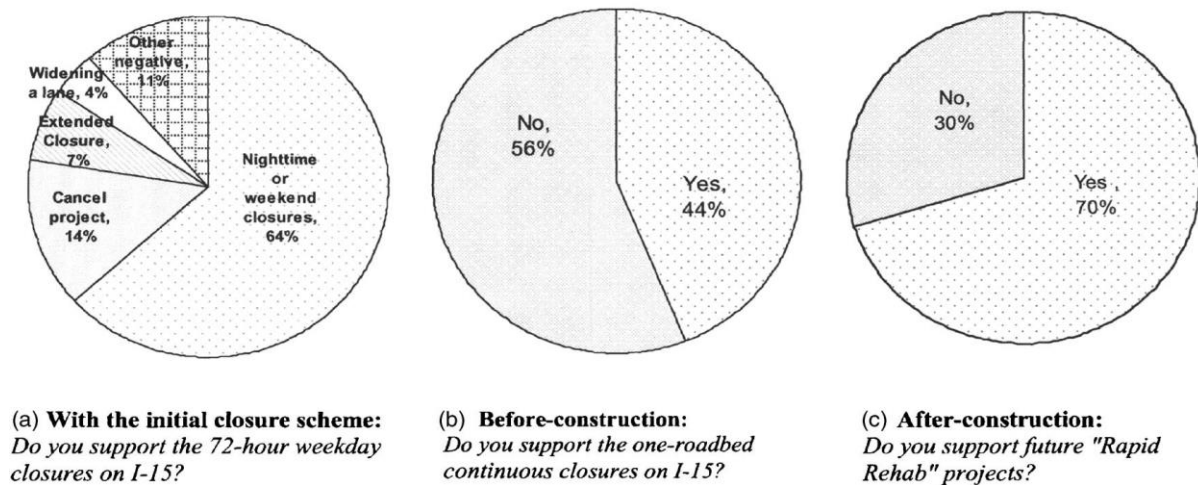


Figure 12-Web Based Survey Results from I-15 Devore Project [27]

3.2.6 Summary of Findings of Accelerated Construction

- Reduce agency and road user cost.
- Reduce congestion during the construction phase.
- Reduce accidents and crossover fatalities during the construction.
- Mitigate GHG emission due reduced disruption to the traffic.
- Excellent for rapid rehabilitation and construction projects.

3.2.7 Case Study iv – Moveable Barrier System (MBS)

Road Zipper System (Moveable barrier system) is composed of a wall of one metre interlocked barrier that are lifted, adjusted and replaced by the help of a transfer machine. It is an innovative way to manage congestion, improve travel times, fuel efficiency and provides flexible and safe space around the work zones. The system is used for managing traffic lanes for both daily traffic and construction applications to create efficient and safe roadways.

MBS manages the lanes on high volume roads, tunnels and bridges to accommodate real time traffic demand where an additional right-of-way may not be available.

MBS is a reusable method and easily moves from one project to another, operates in all weather conditions and helps to eliminated cross-over accidents/fatalities by providing the protection from the oncoming traffic[28], [29].



Figure 13-Moveable Barrier system (MBS)

MBS provides quick build solution for increasing safety and offers green benefits by reducing the GHG emissions to environment with congestions management on busy stretch of highways and bridges. MBS is designed to create a flexible and positive traffic barrier between live traffic and construction zones. It helps to provide additional lane in the construction zone during off peak hours and provide an extra lane to traffic during peak hours. MBS can be used for following applications

1. Highway capacity improvements.
2. Managing traffic lanes (real time demand).
3. Providing express bus lanes.

4. Reversible lanes.
5. Proving HOV lanes during peak hours.
6. Providing extra truck lanes.

Cost Estimation for Moveable Barrier system

As per study done in Australia (Inner West Busway), cost of 1 meter wall piece was around \$500 so, the total cost of the barrier wall for one mile comes to around \$800,000 and the average cost of a transfer machine is around \$ 650,000.

Many countries have already used MBS system. The table below shows summary of projects in different countries which had already used this system.

3.2.8 Summary of Findings of Moveable Barrier System (MBS)

- Save GHG emissions by managing traffic congestion during regular traffic rush hours as well as during construction phase.
- Reduce accidents and crossover fatalities.
- Improve travel time and fuel efficiency.
- Helpful in managing construction sites traffic flow.
- Helpful in accelerated construction projects.

Table 2-Summary of Projects used Moveable Barrier System (MBS)

Project	Problem	Another Alternative	Solution with MBS	MBS Benefits
Interstate 30, Dallas, TX 1991	Peak -rush-hour problem	Add a new Lane	Add an additional lane with MBS	1. Saved 14 minutes per trip. 2. Benefit/Cost ratio 6.5 to 1. 3. Increases vehicle occupancy from 1.1 average in HOV 2.9,
Auckland Harbour Bridge, Auckland, New Zealand, 1990	Traffic increase, 120K vehicles per day, Crossover accidents and fatalities	1.Lights for reversible lane, 2.Bridge was previously expanded to broadest width, 3. Build another bridge	Used MBS as a moveable median	Benefit/Cost ratio 6.8/1, Reduced accidents, and Zero Crossover fatalities.
Pesio Bridge, A6 Motorway, Italy, 2006	During construction, the 2-2 lane configuration was reduced to a 1/1 with buffer zone using lane delineators. Heavy weekend traffic resulted in 6 mi long queue	1/2 configuration using cones caused extended backup on Friday and Sunday and did not provide positive protection.	Construction with MBS 2/1, 1 / 2 configuration.	No traffic queues, Positive protection.
I-15 San Diego, California 2012	Increased delays 80-90min		Express lanes for Buses, Created direct access ramps , Lane management	New, express lanes improved the travel time, connected to new Bus transit center

Chapter 4 – GHG Emissions Results and Associated Impacts

4.1 Introduction

As per the detailed discussions in the previous chapters, the selected strategies are directed at reducing the GHG emissions. This chapter compares the benefits of the various GHG Mitigation Strategies based on available data from the various case studies described in Chapter 3. The summary of benefits from selected case studies are as follows:

1. High Modulus Asphalt Concrete (HMAC).

- Long lasting pavements.
- Reduce maintenance and rehabilitation frequencies.
- Reduce the design thickness of pavement layer by 15 to 20%.
- Allows the use of RAP (Reclaimed Asphalt Pavement).

2. Two Lift Concrete Pavement (2LCP).

- Allows the use of locally available material.
- Allows to accommodate more recycled concrete material.
- Allows to use more Supplemental Cementitious Materials (SCM).

3. Accelerated Construction (24x7).

- Minimal traffic disruption.
- Cut down traffic delays and congestion.
- Reduced agency cost and road user cost.
- Reduce GHG emissions due to reduced construction time.

4. Moveable Barrier System (MBS).

- Manages congestion during regular traffic operations as well as around the construction zones.
- Improves travel time and fuel efficiency of the commuters.
- Increase safety around the construction zones and during peak rush hours.

4.2 GHG Calculations from the Different Strategies.

All the strategies and studies involve calculating the reductions of GHG emissions namely carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and other greenhouse gases. GHG emissions depend upon many factors as discussed in previous chapters. The factors taken into account involve replacement of cement with SCMs, aggregate production at quarries and pits, material transportation and GHG emissions related to vehicle speeds and associated traffic congestion. These factors directly and indirectly impact the production of GHG emissions on the environment. The above mentioned case studies highlight the importance of these factors for the GHG reductions. Selected factors and the data given in different case studies are evaluated from a different prospective, so that the use of these factors shows direct positive impacts on the environment. Calculation are as shown below.

4.2.1 GHG Savings Related to Cement Consumption and Production.

Different case studies and different calculation methods for GHG emissions were utilized in this analysis. However all the various assessments resulted in similar findings. Findings from the different studies related to cement production and consumption are incorporated in this section as follows:

- Caltrans [30] used approximately 186,000 tons (fly ash and blast furnace slag) in 2010 while constructing road and bridges in California. Caltrans reported by using 186,000 tons of SCMs (Supplemental Cementous material) they saved more than 47,000 tons of GHG emissions, which is equivalent of taking 9100 vehicles off from the road for a year. So from the Caltrans' data the following can be concluded :

- Replacing 1 ton of SCMs will save 0.25 ton (227 kg) GHG emissions.
- One vehicle (Passenger car) produces 5.2 tons of GHG emissions in year.
- MTO also states that the slag and fly ash are considered as a direct replacement for cement which leads to direct GHG reductions. Depending on the standard concrete mix design MTO reported that replacing Cement with SCMs will reduce 10- 30 % CO₂ from environment [21].

GHG Emissions (g CO₂e/year) = **Carbon Content of Fuel** (g CO₂e/MJ) x **Vehicle Energy Intensity** (MJ/Km) x **Activity** (Km/year)

MTO uses the formula as mentioned above to calculate the GHG Emissions related to traffic. MTO also justifies in Value engineering study report [21] that one passenger car produces 4.6 tones (5.1 tons) of CO₂ in one year.

- Studies completed by the World Bank used a tool name “Changer”, developed by International Road Federation (IRF) to calculate the GHG emissions for road construction and rehabilitation process. This tool also indicates that replacing cement with other SCMs will save the GHG emissions by 1:1. Changer assumes that using 1 ton of cement produces approximately 1057 t CO₂ and the CO₂ emissions drops to 825 t CO₂ by using the cement with 25 % blast furnace slag which is equivalent to 22 % reduction in GHG emissions. CO₂ emissions drops to 580 t CO₂ by using cement 50 % blast furnace slag. This is equivalent to the saving of 45 % GHG emissions to the environment [31]. So it can also be calculated that:
 - Replacing 1 % cement with 1 % SCM will help to reduce 1% of GHG emissions.

In summary, it can be concluded that by replacing 1 ton of cement with supplemental cementitious materials it will save 0.25 tons GHG emissions.

Table 3-Summary of GHG Savings Related to Cement Production and Consumptions

Replacement of	GHG Savings	Reference
1 ton SCM	0.25 tons (22kg)	DOT California
1% SCM	1% GHG gases	Ministry of Transportation Ontario
1 ton Cement	1057 t CO ₂ eq.	International Road Federation (IRF)

4.2.2 GHG Savings Related to Aggregates Production.

Studies indicate that the recycled aggregates are more economical to produce and have very little effect on the environment and climate change such as contributing to the depletion of the ozone layer, acidification of the environment, respiratory effects, aquatic and human toxicity compared to natural and crushed aggregates as shown in Figure 14. Figure 14 shows a comparison of the environmental damage from fine aggregates production from different sources like natural river sand (RS), natural fines from crushed stone (CS), recycled fines from construction and demolition waste (C&D) and recycled fines from waste glass (WG). The results revealed that as compared to natural coarse aggregates, recycled coarse aggregates produced from construction and demolition waste reduces 65% greenhouse gases (GHGs) emission with a saving of 58% non-renewable energy consumption.

For production of fine aggregates, it is estimated that approximately 341 MJ of energy is required to produce 1t of fine aggregates from river sand which generates 23 kg CO₂ eq. GHG emissions. Similarly, 518 MJ of energy is required to produce 1t of manufactured fines from crushed stone. This process emits approximately 33 kg CO₂ eq. GHG emissions whereas recycle fine aggregates produce only 12 kg CO₂ eq. GHG emissions. From the data it can calculate the following:

- Crushed fine aggregates produce approximately 30 % more GHG emissions than natural fine aggregates.

- Recycled fines produce approximately 47% less GHG emissions than natural fines and 63% less GHG emissions than crushed fine aggregates.

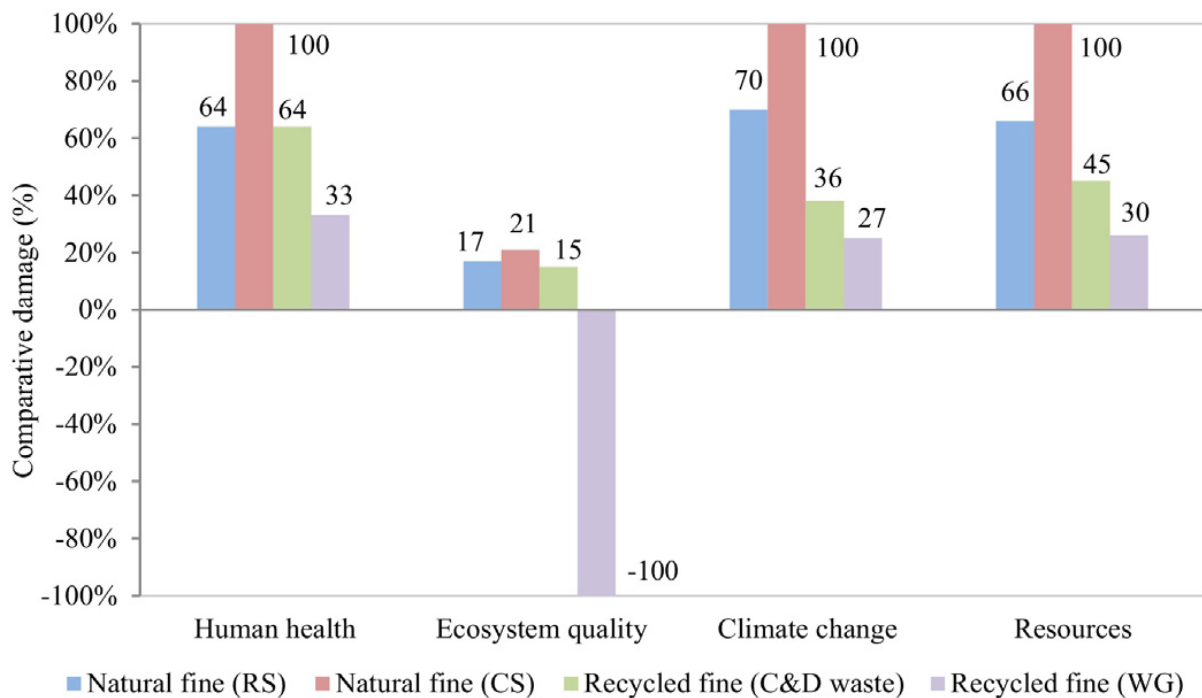


Figure 14-Comparison of Environmental Damage Assessment for fine Aggregates Production. [32]

It is also estimated that the production of one ton of coarse aggregates emits 32 Kg CO₂ eq. GHG emissions. Whereas the coarse recycled aggregates produces 11 Kg CO₂ eq. GHG emissions. So it can be concluded as:

- Recycled coarse aggregates produce approximately 65 % less GHG emissions than coarse aggregates from crushed stones.

Table 4-Summary of GHG Savings related to Aggregate Production

Materials	GHG produced (Kg CO₂ eq.)
Natural Fine Aggregate	23
Manufactured Fine Aggregate	33
Crushed Coarse Aggregate	32
Recycled Coarse Aggregate	11
Recycled Fine Aggregate	12

4.2.3 GHG Emissions Related to Material Handling and Transportation.

Few studies calculated that transposition of aggregates from the quarry/pit to the production plant location and then the transportation to the construction site. This contributes approximately 30 % to 70 % of the total GHG emissions produced. This depends greatly on the distance between the location of the quarry or source of material, the plant or processing location and construction site. In most of the scenarios, virgin materials are moved/handled at least 2-3 times before they reach the construction site. Whereas, recycled aggregates often reduces the handling from quarry locations to the production plants and in some cases if in-situ recycling is completed it never moves off the site. Similarly, data shown below in Figure 15 shows that recycled aggregates can save 35-50% energy consumption from transportation process only [32]. It is also indicated that for the change in every 10% of transportation distance there is approximately 6% change of the total GHG emissions, similarly for every 20% change of transportation distance will impact the GHG emissions by 12 % [32].

Table 5-GHG Savings Related to Aggregate Production & Transportation

Energy consumption MJ/t			
	Extraction & Handling	Total Transportation Process	Total
Natural Fine (River Sand)	98	242	340
Natural Fine (Crushed Sand)	177	341	518
Recycled fines	84	151	235
Natural coarse (Crushed Stone)	155	341	496
Recycled coarse	84	127	211

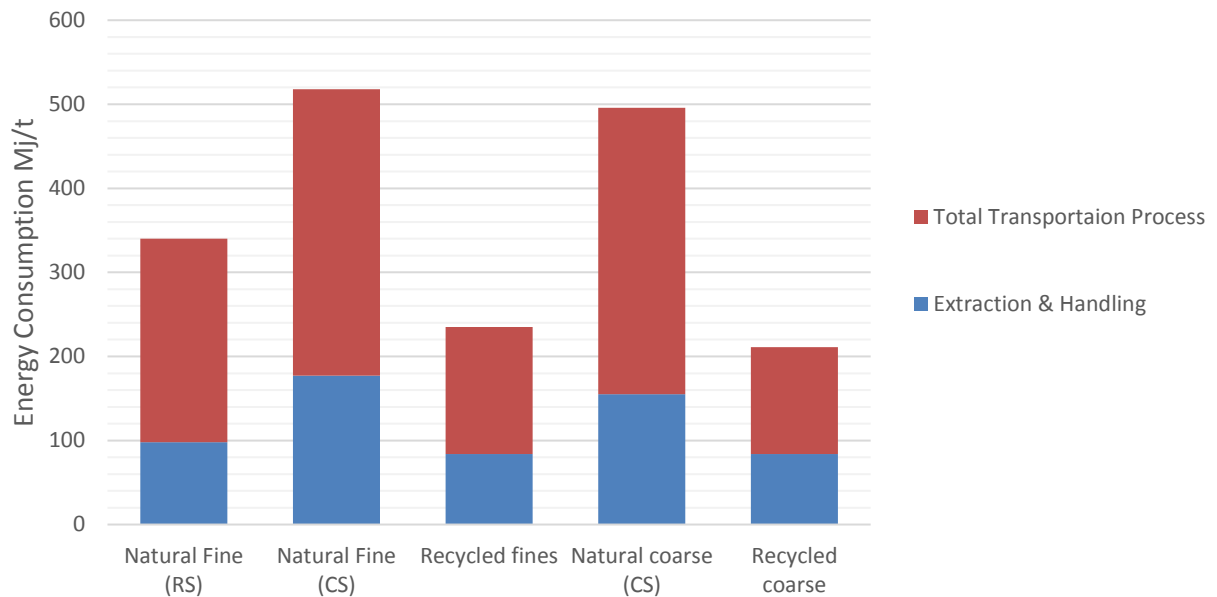


Figure 15-Energy Consumption for Aggregates Production.

Similarly, the World Bank has evaluated GHG emissions and established a tool kit for developing countries related to GHG emissions from different construction activities. The majority of the GHG emissions are related to materials used in construction and transportation of the materials. Construction activities are shown in Table 6 and Figure

16. Transportation activities contribute almost 30% GHG emissions during the construction phase for all type of roads [31].

Table 6-GHG Emissions (%) for Construction Activities.

GHG Emissions by each activity (%)			
	Transportation	Material	Machines
Expressway	31.0	65.6	3.4
National Road	29.6	65.8	4.6
Provincial Road	32.0	54.0	14.0

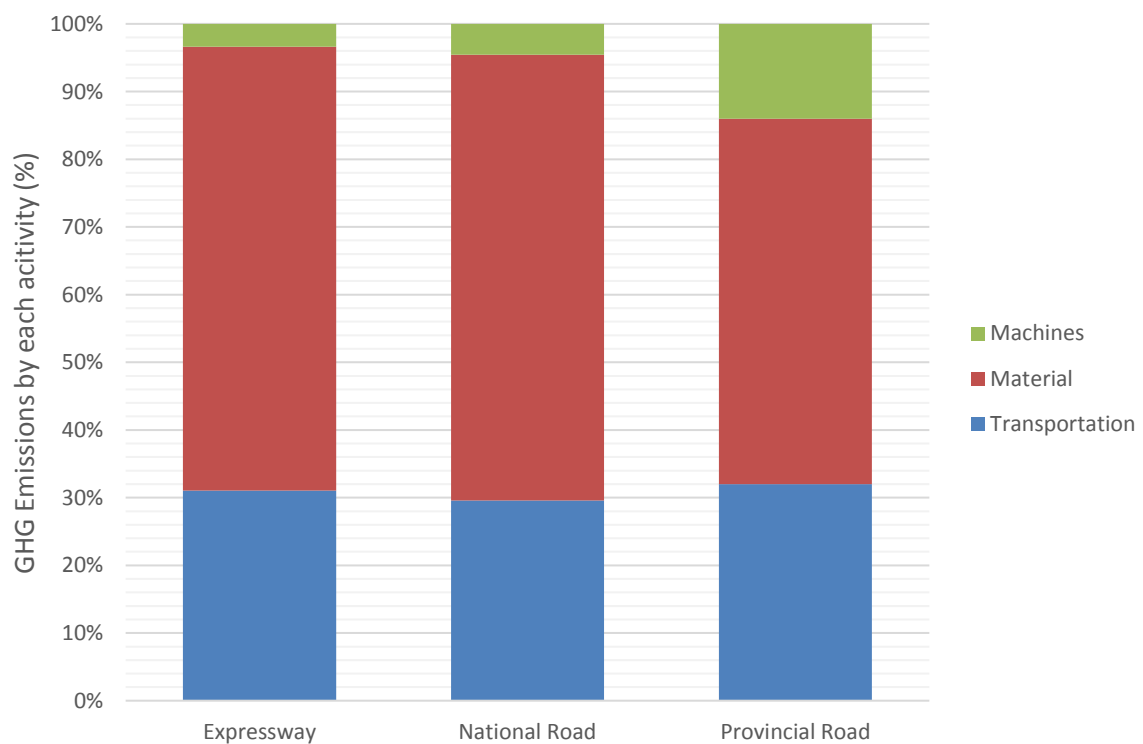


Figure 16-GHG Emissions (%) for Construction Activities.

4.2.4 GHG Emissions Related to Vehicles

Many studies are done to calculate the GHG emissions related to vehicle emissions, Ministry of Transportation Ontario (MTO) calculated the GHG emissions produced by the truckload while handling the material back and forth from the construction site under Windsor Tunnel Plaza project done in 2015 [21]. Study recommends that the GHG emissions from the diesel heavy-duty trucks used during the construction are

- $2 \text{ MJ/t-Km} \times 70 \text{ g CO}_2/\text{MJ} = 140 \text{ g CO}_2/\text{t-Km}$; or
- $33 \text{ L/100 Km} \times 2700 \text{ g CO}_2/\text{L} = 890 \text{ g CO}_2/\text{Km}$

Based on the above recommendations it is concluded that by reducing the number of truck trips from the construction site will reduce GHG emissions by approximately 890 g CO₂/ Km.

The World Bank tool kit for developing countries, and the Software “VicRoads” was used to calculate the intensities of emissions during construction activities. The study recommends that the medium truck operated by diesel fuel produces 0.83 Kg eq. CO₂ per kilometer and similarly heavy duty diesel truck produces 1.58 Kg eq. CO₂ per kilometer [31].

The GHG emissions also depends on the speed of the vehicles as well. Traffic speed and congestion plays an important role in the GHG emissions [21]. Many studies indicated that too slow and too fast traffic produced more GHG emissions than the normal speed [21,29].

Ministry of Transportation Ontario (MTO) and Caltrans (Department of Transportation California) presented the study under Environmental policy and showed effect of congestion on GHG emissions as shown in Figure17.

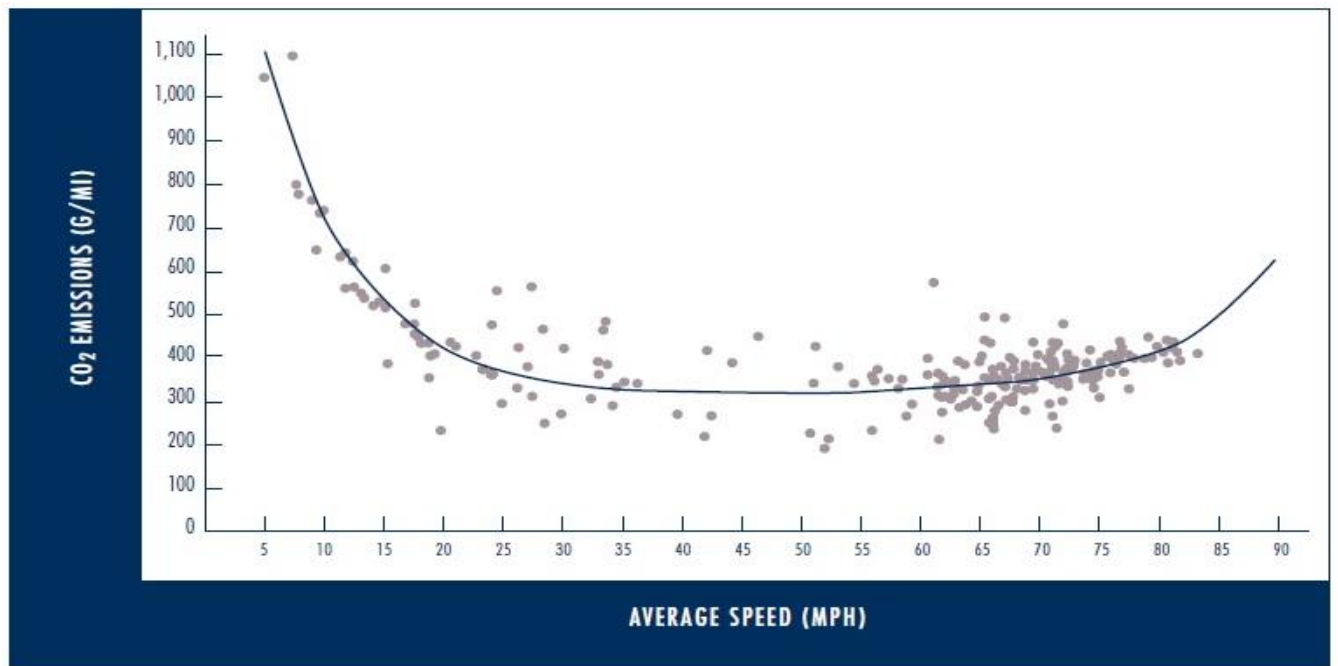


Figure 17-Effect of Congestion on GHG Emissions [21].

Figure17 describes that the vehicles speed 50-100 Km /h (30-60 mph) range produces minimum GHG emissions. When the travel speed dropped below 40 Km/h (25 mph), GHG emissions increases significantly. So, managing congestion can put a huge impact on GHG savings. Table 7 shows the results evaluated from different strategies for vehicle transportation.

Table 7-GHG Savings Related to Vehicles Transportation

Type of Vehicle	GHG Produced	Reference
1 Medium Construction Truck	890 g CO ₂ / Km	Ministry of Transportation Ontario
1 Medium Construction Truck	830 g CO ₂ / Km	Vic Roads
1 Heavy Construction Truck	1580 g CO ₂ / Km	Vic Roads
Passenger Car	5.1 tons /Per year	Ministry of Transportation Ontario
Passenger Car	5.2 tons /Per year	DOT California

4.3 GHG Savings with Selected Strategies.

Each selected strategy from the various jurisdictions helps to reduce the GHG emissions. Studies suggest that improved methods of saving GHG emissions related to cement production, virgin aggregates, material handling, managing travel speed and congestions techniques as compared to the traditional practices. The calculations shown below are based on the data selected from the case studies discussed above.

High Modulus Asphalt Concrete (HMAC)

High Modulus Asphalt Concrete helps to reduce maintenance and rehabilitation frequencies thereby reducing the GHG emissions from transportation activities during the construction. As per the above discussion, transportation activities contribute approximately 30% of total GHG emissions during construction phase. Less maintenance activities means less consumption of virgin aggregates which leads to another 50-60% reduction of GHG emissions as compared to conventional maintenance activities. Also, it has reduced congestion periods, because of less interruptions to the traffic due to reduced maintenance frequencies. HMAC technique helps to reduce the pavement thickness by 15-20%. The 15% reduced thickness leads to the saving of approximately 171 tons of aggregates for 1 Km, 60mm thick, two lane road (7.5m) as compared to conventional SP 12.5 FC2 mix. So this saves approximately 5472 kg CO₂ eq. GHG emissions as per 4.2.2 (@ 32 kg CO₂ eq. GHG emissions per ton) from the aggregate production only. It means saving 6 (30t capacity) truck trips to haul the material. Reducing the truck trips by 6 will save approximately 498 kg CO₂ eq. GHG emissions by assuming total 100 Km distance (back and forth) from the quarry to plant and then plant to construction site.

HMAC also allows to accommodate up to 35% reclaimed asphalt pavement (RAP) into the mixes which means savings 35% of virgin aggregates and reduce the GHG emissions by approximately 7022 Kg CO₂ eq. GHG emissions from material savings and saving of approximately 1160 kg CO₂ eq. GHG emissions from

transportation.(assuming same parameters as above).Table 8 shows the summary of finding as per the calculations above.

Table 8-Summary of Benefits for High Modulus Asphalt Concrete (HMAC)

Benefits	Saving	GHG Saving (kg CO ₂ eq.)
Reduced Thickness	Virgin Aggregates	5472
Recycled asphalt	up to 35%	7022
Transportation & Production	Virgin Aggregates	1658

Two Lift Concrete Pavement (2LCP).

Two Lift Concrete Pavement provides an excellent opportunity to make concrete pavements sustainable with reduction in GHG emissions. As compared to conventional 35 MPA road pavement 2LCP allows to accommodate locally available material for 90% of the designed thickness.

Standard 35 MPA slip formed road mix contains approximately 15 % (350 Kg/ m³) of cementous material, so two lane 1 Km concrete road (7.5 m wide and 0.28 m thick) will need 800 tons (724500 Kg) cement in the mix. This will produce approximately 202 tons of GHG emissions as per above discussion in 4.2.1. Presently, by using 100% crushed aggregates to achieve the desired strength, aggregates are 85% (1920 Kg/ m³) of the mix. To construct 1 Km of concrete pavement this will require 4450 tons of aggregates to produce approximately 157 tons CO₂ emissions.

To transport the aggregates from quarry to site will need approximately 150 trips (30t) and will produce 12450 Kg CO₂ eq. GHG emissions by assuming total 100 Km distance (back and forth).

By using the 2LCP technique, it will use locally available material in the bottom lift (90% of design thickness), which will reduce the haul distance 60-70% and will reduce the GHG emissions approximately 3750 Kg CO₂ eq. GHG from the transportation process only.

2LCP also allows for up to 50% of recycled materials that will save GHG emissions by 78000 kg CO₂ eq. from the aggregate production and 5000 kg CO₂ eq. from the transportation of the material for 1 Km concrete pavement.

2LCP also provides the opportunity to use up to 40 % of SCMs in the mix without compromising the overall strength of the pavement. Using 40% of SCM will save 35-40 % of GHG emissions which is equal to replacing 290 tons of cement and saves 72 tons of GHG emissions for 1 Km stretch of concrete pavement. Table 9 shows the findings of GHG savings as per the calculation above.

Table 9-Summary of Benefits of Two Lift concrete Pavement (2LCP)

Benefits	Saving	GHG Saving (kg CO₂ eq.)
Local Aggregates	Virgin Aggregates	90,000
	Transportation	3,750
RCA	Virgin Aggregates	78,000
	Transportation	5,000
SCM	Cement	65,000

Accelerated Construction (24x7) & Moveable Barrier System (MBS)

Both of these strategies are used to minimize the disruption of traffic during the construction and service phase of the pavement. Moveable barrier system is used to provide safe work zones during construction phase and manages the congestions during regular traffic operations as well as around the construction zones. As noted in the I-15 Devore project, with accelerated construction techniques Caltrans was able to complete the project in two 9 days continuous closures, instead of 10 months of traditional night time construction. Moveable barrier system was one of the techniques used during the project to manage the peak hour traffic during construction. So, with accelerated construction, Caltrans was able to save approximately 180 construction

days. That means 180 less days of traffic congestion associated with construction closures.

As described in Figure 17 vehicles produce at least (325 g/Km) GHG emissions when vehicle's speeds are between 50-100 Km/h (30-60 mph). GHG emissions increased significantly (500 g/Km) when speed drops to 25 Km/h.

Average daily traffic on the Devore project had peak hourly volumes of 5500 vehicles per direction during the weekdays and the project was approximately 5 Km long [26]. So with accelerated construction technique Caltrans was able to provide normal traffic conditions for 180 days which saved approximately 955 tons (calculations as done using data from Figure 17) of GHG emissions per direction as compared to the traditional construction closure techniques.

Similarly, moveable barrier system improve travel time and fuel efficiency of the commuters. It also helps to manage the congestions during peak hours. By improving the traffic speed by 10 Km /h this will save 50 g/ Km CO₂ emissions (as per the clause 4.2.4).

Annual average daily traffic of Hwy 401 for 2.7 Km stretch between Hwy 400 to Islington Ave is more than 400,000 [33]. So, improving the traffic speed by 10 Km /h it will be able to save 54000 kg CO₂ eq. GHG emissions. These techniques helps to improve the traffic speed and manages congestion. It also helps to reduce the GHG emissions produced by the traffic.

In addition to congestion management, major benefit of implementing MBS on a busy highway is to reduce accidents and crossover fatalities.

4.4 Life Cycle Analysis (LCA) Calculation.

The Athena software tool had been used to calculate the life cycle analysis and perform the comparative studies between the strategies. This software provides life cycle analysis on manufacturing materials, road constructions and maintenance life cycle stages of the pavements.

This software is very helpful as it allows its users to include each and every equipment used to make any specific pavement, such as sub-base and base granular material,

hot mix, warm mix asphalt and user- specified concrete mix design. Athena makes the comparison between different design techniques so easy thereby allowing quick and easy comparison among them.

This software was made possible by support from the Cement Association of Canada and Athena Institute members.

The earlier software prototype and beta version were developed in association with Transportation Engineers at Morrison Hershfield, and was funded by Environment Canada[34].

4.4.1 LCA Calculations for High Modulus Asphalt Concrete (HMAC)

Athena Pavement LCA software has been used to perform the side by side comparatives for conventional SP12.5 FC2 and HMAC mixes. Assumptions were made for the following design parameters such as design proportions, rehabilitation activities for 50-year design life to calculate Life Cycle Analysis (LCA) for both the mixes:

- ✓ 1 Km, 2 lane road with lifts of granular and asphalt pavement.
- ✓ Base course as SP19mm mix.
- ✓ Granular A and Granular B.

Table 10-Design Proportions

Parameters	SP12.5FC2	HMAC
Design Thickness	60mm	48mm
Asphalt Content	5.3%	6%
Coarse aggregate	34.07%	22%
Fine aggregates	60.63%	42%
Recycled Asphalt	0%	30%

Table 11-High Modulus Asphalt Concrete (HMAC) Rehabilitation Schedule

Year After Initial Construction	Expected Lifespan [Years]	Activity Type	Description
10	5	Asphalt Rout & Seal	Rout & Seal
20	15	Asphalt Partial Depth Reclamation	Mill 40mm
20	15	Asphalt Paving	Resurface w/ HMAC
25	5	Asphalt Rout & Seal	Rout & Seal
30	5	Asphalt Partial Depth Reclamation	Spot Repairs
35	13	Asphalt Full Depth Reclamation	Resurface SP19
35	13	Asphalt Partial Depth Reclamation	Mill 90mm
35	13	Asphalt Paving	Resurface w/ HMAC
48	12	Asphalt Full Depth Reclamation	Full Depth Repair
48	12	Asphalt Partial Depth Reclamation	Mill 40mm
48	12	Asphalt Paving	Resurface HMAC

Table 12-Rehabilitation Schedule for Pavement with SP 12.5 FC2 mix.

Year After Initial Construction	Expected Lifespan [Years]	Activity Type	Description
5	5	Asphalt Rout & Seal	Rout & Seal
10	5	Asphalt Partial Depth Reclamation	Spot Repairs
10	5	Asphalt Rout & Seal	Rout & Seal
20	15	Asphalt Partial Depth Reclamation	Mill 40mm
20	15	Asphalt Paving	Resurface w/ SP12.5FC2
25	5	Asphalt Rout & Seal	Rout & Seal
30	5	Asphalt Partial Depth Reclamation	Spot Repairs
35	13	Asphalt Full Depth Reclamation	Mill 90mm
35	13	Asphalt Partial Depth Reclamation	Resurface w/ SP19
35	13	Asphalt Paving	Resurface w/ SP12.5FC2
40	8	Asphalt Rout & Seal	Rout & Seal
45	5	Asphalt Partial Depth Reclamation	Spot Repairs
48	12	Asphalt Full Depth Reclamation	Full Depth Repair
48	12	Asphalt Partial Depth Reclamation	Mill 40mm
48	12	Asphalt Paving	Resurface w/ SP12.5FC2

With the assistance of Athena Pavement LCA software, HMAC and SP12.5FC2 were compared for global warming potential, acidification potential, ozone depletion potential, total primary energy consumption, non-renewable energy consumption and fossil fuel consumption, as shown in Table 13.

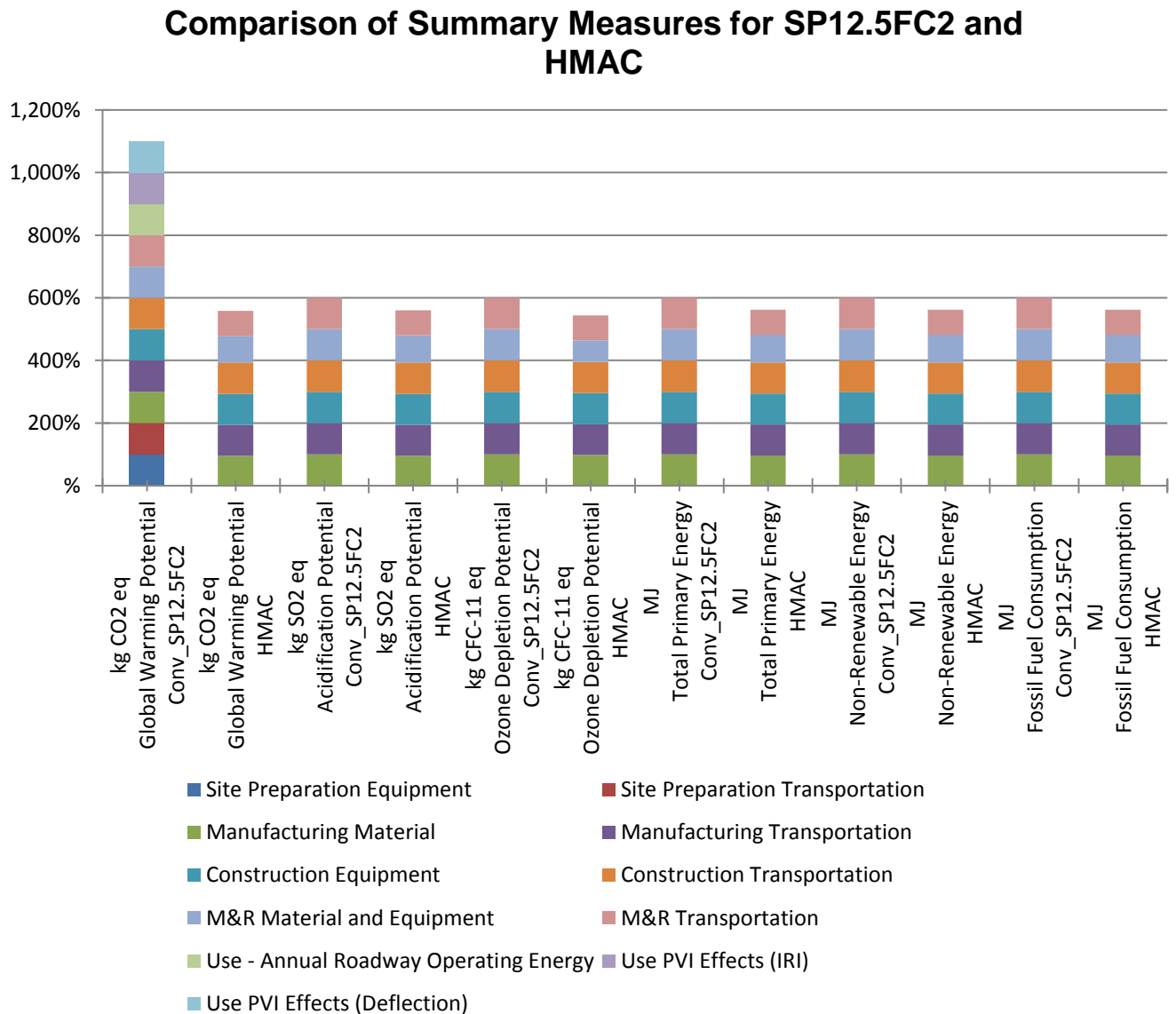


Figure 18-Summary Comparison of GHG Potential for SP 12.5FC2 and HMAC Mixes

Table 13-Comparison of Summary Measures by Life Cycle Stage Report [SP12.5FC2 and HMAC]

	Name	Unit	Manufacturing			Construction			Maintenance			Embodied Effects		
			Material	Transportation	Total	Equipment	Transportation	Total	Material and Equipment	Transportation	Total	Material and Equipment	Transportation	Total
Conv_SP12.5FC2	Global Warming Potential	kg CO2 eq	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HMAC	Global Warming Potential	kg CO2 eq.	96%	98%	97%	99%	99%	99%	85%	80%	84%	92%	96%	93%
Conv_SP12.5FC2	Acidification Potential	kg SO2 eq.	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HMAC	Acidification Potential	kg SO2 eq	96%	98%	97%	99%	99%	99%	87%	80%	86%	92%	96%	94%
Conv_SP12.5FC2	Ozone Depletion Potential	kg CFC-11 eq	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HMAC	Ozone Depletion Potential	kg CFC-11 eq	98%	98%	98%	99%	99%	99%	69%	80%	69%	94%	96%	94%
Conv_SP12.5FC2	Total Primary Energy	MJ	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HMAC	Total Primary Energy	MJ	97%	98%	97%	99%	99%	99%	88%	80%	88%	93%	96%	93%
Conv_SP12.5FC2	Non-Renewable Energy	MJ	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HMAC	Non-Renewable Energy	MJ	97%	98%	97%	99%	99%	99%	88%	80%	88%	93%	96%	93%
Conv_SP12.5FC2	Fossil Fuel Consumption	MJ	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
HMAC	Fossil Fuel Consumption	MJ	97%	98%	97%	99%	99%	99%	88%	80%	88%	93%	96%	93%

Conclusions from the results derived from Athena Pavement LCA software, the following things were concluded:

HMAC shows approximately 3% better results for global warming potential, acidification potential, ozone depletion potential, total primary energy consumption, non-renewable energy consumption and fossil fuel consumption as compared to SP12.5FC2 mix during the manufacturing process. Approximately, 3-4% from the material production and 2-3% from the transportation of the virgin materials. Similar results were found for the construction process of the mixes as well.

HMAC showed significant difference during the service life of the pavement and the maintenance phase. With HMAC mixes shows 30% less effect on ozone layer depletion and 15-20% better for remaining global warming, acidification potentials and energy consumptions.

4.4.2 Two Lift Concrete Pavement (2LCP).

Athena Pavement LCA were also performed on 2LCP pavement and conventional 30 MPa concrete pavement design. Following assumptions were made for the parameters like, design proportions, rehabilitation activities for 50-year design life to calculate Life Cycle Analysis (LCA) for both the mixes:

- ✓ 1 Km, 2 lane road with lifts of granular, and concrete pavement.
- ✓ 1 lift for conventional concrete pavement and 2 lifts of 2LCP.
- ✓ Granular A

Table 14-Design Proportion

Parameters	Conventional 30 MPa	2LCP
Design Thickness	280mm	280 mm (250 mm bottom lift)
Portland Cement	12.11%	9.11%
Coarse aggregate	47.83%	22.54% (natural)
Fine aggregates	30.44%	15.73% (natural)
Slag Cement	3.10%	6.10%
RCM aggregates	0%	40%

Table 15-Conventional 30Mpa Rehabilitation Schedule.

Year After Initial Construction	Expected Lifespan [Years]	Activity Type	Description
12	13	Concrete Partial Depth Repair	Partial Depth Repair
12	13	Concrete Seal Joint	Reseal Joints
25	15	Concrete Full Depth Repair	Full Depth Repair
25	15	Concrete Partial Depth Repair	Partial Depth Repair
25	15	Concrete Seal Joint	Reseal Joints
25	15	Concrete Texturization	Diamond Grinding
40	15	Concrete Full Depth Repair	Full Depth Repair
40	15	Concrete Partial Depth Repair	Partial Depth Repair
40	15	Concrete Seal Joint	Reseal Joints
40	15	Concrete Texturization	Diamond Grinding

Table 16-2LCP Rehabilitation Schedule

Year After Initial Construction	Expected Lifespan [Years]	Activity Type	Description
12	13	Concrete Partial Depth Repair	Partial Depth Repair
12	13	Concrete Seal Joint	Reseal Joints
25	15	Concrete Full Depth Repair	Full Depth Repair
25	15	Concrete Partial Depth Repair	Partial Depth Repair
25	15	Concrete Seal Joint	Reseal Joints
25	15	Concrete Texturization	Diamond Grinding
40	15	Concrete Full Depth Repair	Full Depth Repair
40	15	Concrete Partial Depth Repair	Partial Depth Repair
40	15	Concrete Seal Joint	Reseal Joints
40	15	Concrete Texturization	Diamond Grinding

With the help of Athena Pavement LCA software, Conventional 30 MPa and 2LCP were compared for global warming potential, acidification potential, ozone depletion potential, total primary energy consumption, non-renewable energy consumption and fossil fuel consumption, as shown in table 17.

Table 17-Comparison of Summary Measures by Life Cycle Stage Report [2LCP and Conventional 30Mpa]

Project Name	Name	Unit	Manufacturing			Construction			Maintenance			Embodied Effects		
			Material	Transportation	Total	Equipment	Transportation	Total	Material and Equipment	Transportation	Total	Material and Equipment	Transportation	Total
2LCP 30Mpa	Global Warming Potential	kg CO2 eq	83%	81%	83%	159%	100%	134%	100%	100%	100%	90%	88%	90%
Conv_30Mpa_20% Slag	Global Warming Potential	kg CO2 eq	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2LCP 30Mpa	Acidification Potential	kg SO2 eq	93%	81%	91%	159%	100%	134%	100%	100%	100%	101%	88%	98%
Conv_30Mpa_20% Slag	Acidification Potential	kg SO2 eq	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2LCP 30Mpa	Ozone Depletion Potential	kg CFC-11 eq	111%	81%	111%	159%	100%	134%	100%	100%	100%	109%	88%	109%
Conv_30Mpa_20% Slag	Ozone Depletion Potential	kg CFC-11 eq	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2LCP 30Mpa	Total Primary Energy	MJ	90%	81%	89%	159%	100%	134%	100%	100%	100%	98%	88%	96%
Conv_30Mpa_20% Slag	Total Primary Energy	MJ	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2LCP 30Mpa	Non-Renewable Energy	MJ	91%	81%	90%	159%	100%	134%	100%	100%	100%	99%	88%	97%
Conv_30Mpa_20% Slag	Non-Renewable Energy	MJ	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2LCP 30Mpa	Fossil Fuel Consumption	MJ	91%	81%	89%	159%	100%	134%	100%	100%	100%	99%	88%	97%
Conv_30Mpa_20% Slag	Fossil Fuel Consumption	MJ	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Comparison of Summary Measures by Life Cycle Stage

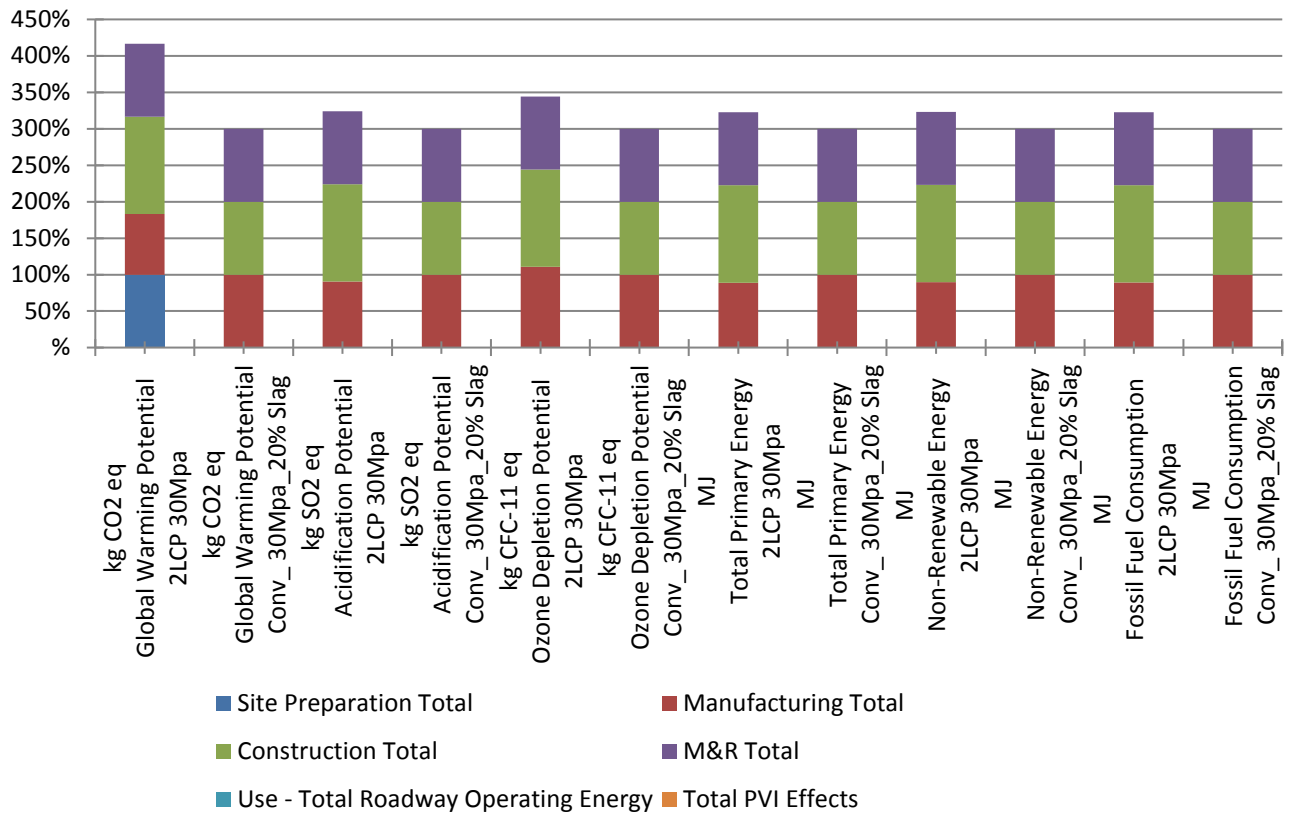


Figure 19-Summary Comparison of GHG potential for 2LCP and Conventional 30MPa Concrete Mixes.

The following results were concluded from the Athena Pavement LCA software.

Due to difference in material used and different construction processes for both mixes. Results from Athena software showed clear picture of GHG Emission potentials for each phase of both the mixes. For the manufacturing and transportation of virgin aggregates 2LCP strategies showed 10-20% less effect on the environment.

As it needs more equipment to pave the 2LCP pavement, Athena results shows the 2LCP pavement has approximately 35% worst effect on the environment during the construction process only.

Overall, Athena software shows under embodied effects for both materials, equipment and transportation. 2LCP pavement has 10-12% less effect on the environment (global warming potential, acidification potential, Ozone depletion potential, total primary energy, non-renewable energy and fossil fuel energy). Maintenance phase did not show any difference for both the strategies as there is no such significant difference of rehabilitation or maintenance schedule for the strategies.

Chapter 5 Conclusions

Road infrastructure plays a critical role in the economy and it contributes to the quality of life. Rapid growth in the transportation and its infrastructure sector made the transportation industry, the fastest growing source of Greenhouse Gas (GHG) Emissions. When transportation infrastructure ages and deteriorates with time it needs major rehabilitation and maintenance. Construction and maintenance of road networks have major impacts on the environment and on the quality of life. Ontario faces challenges in maintaining road transportation infrastructure with limited availability of funds for maintenance and repairs. The exchange of knowledge and expertise from other developed countries around the world provides the opportunities to evaluate and analysis new techniques and strategies of building, maintaining and reconstructing road infrastructure to mitigate the GHG emissions.

This thesis summarizes the innovative practices adopted in transportation sector by other countries to improve the pavement sustainability. The research is to quantify pavement sustainability to mitigate the GHG emissions by implementing new strategies based on their feasibility in term of costs, level of adaptation and industry's existing capacity in Ontario.

Four strategies were investigated and evaluated based on their feasibility of implementing innovative GHG mitigation strategies in the highway design, construction and maintenance. Strategies were focused to improve the traffic congestion during the construction, maintenance and operational phases of the road to improve travel time and fuel efficiency. Accelerated construction technique helped to cut agency and road user cost by reducing the congestion during the construction phase, it also helps to reduce the 180 construction days at I-15 Devore project. Thus showed the saving of 955 tons of GHG emissions per direction as compared to conventional construction closure techniques.

Moveable Barrier System (MBS) also showed huge saving of GHG emissions by eliminating the long traffic queues during the peak rush hour on a busy highway. By improving the traffic speed by 10 Km /h on Ontario's Highway 401 will save 54000 kg CO₂ eq. GHG emissions generated from traffic. MBS also helps to reduce accidents and crossover fatalities.

High Modulus Asphalt Concrete (HMAC) reduce maintenance and rehabilitation frequencies. Results showed that HMAC design saves the usage of virgin aggregates and allows to incorporate up to 35% of RAP material. HMAC technique also makes road pavement resistance to permanent deformation and fatigue. This saved GHG emissions from transportation activities during the construction. Results indicated that replacing the conventional asphalt mix with HMAC mix will save approximately 14000 kg CO₂ GHG emissions as described in Table 8.

HMAC results from the Athena software also showed approximately 3% better results for global warming potential, as compared to SP12.5FC2 mix during the manufacturing process. Approximately, 3-4% from the material production and 2-3% from the transportation of the virgin materials. HMAC showed better results during the service life of the pavement and the maintenance phase. HMAC mixes showed 30% less effect on ozone layer depletion and 15-20% better for remaining global warming, acidification potentials and energy consumptions.

Two Lift Concrete Pavement (2LCP) technique showed an excellent alternative to making concrete pavements sustainable and reducing GHG emissions. 2LCP technique allows to accommodate more Recycled concrete aggregates, supplementary cementitious material and locally available aggregates for 90% of the designed thickness. There is a saving of approximately 250,000 kg CO₂ emissions by replacing conventional 35 MPA concrete mix with 2LCP mix for one 1 Km road pavement as described in Table 9.

Analysis done with Athena software 2LCP strategies showed 10-20% less effect on the environment for the manufacturing and transportation of virgin aggregates.

Though 2LCP technique need more equipment for the paving operations, but overall 2LCP pavement has 10-12% less effect on the environment and GHG emissions.

All the four selected strategies showed very promising results for saving of GHG emissions in the transportation infrastructure. All of these strategies will not have any equipment barrier and require major changes to the existing construction capacity of Ontario. As of now, industry has very limited knowledge of these strategies for the implementation in Ontario's construction practice. Results from different studies also showed that with experience, knowledge and time these strategies will show huge benefit to save GHG emissions from transportation planning, construction, maintenance and rehabilitation activities.

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